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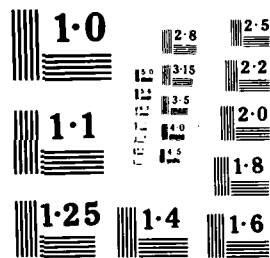
TOPOGRAPHIC CONTROLS ON RAINFALL AND RUNOFF(U)
HUDDERSFIELD POLYTECHNIC (UK) DEPT OF GEOGRAPHY
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TOPOGRAPHIC CONTROLS ON RAINFALL AND RUNOFF

by

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Timothy P Burt +

Susan E Cooper *

A report submitted by:

The Department of Geographical Sciences
The Polytechnic
Queensgate
Huddersfield HD1 3DM
United Kingdom

To:

US Army European Research Office
London
United Kingdom

March 1986

Current addresses:

+ Dr T P Burt
School of Geography
The University of Oxford
Oxford, OX1 3TB
United Kingdom

* Mrs S E Morris
Institute of Hydrology
Wallingford
Oxon, OX10 8BB
United Kingdom

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conditions and their associated rainfall systems, and with the effects of that rainfall on flood discharge of local streams.

The first chapter reviews rainfall variation in time and space and emphasises the need for a distributed approach to rainfall studies. Chapter 2 describes the field site and instrumentation, in particular the errors associated with raingauges and the methods adopted to minimise those errors. The third chapter is concerned with the design of the raingauge network and includes the use of a Computer-Aided Experimental Design. The fourth chapter is a statistical analysis of daily rainfall patterns in the study area, and establishes the clear dominance of orographic rainfall distributions for the study area at the "daily" timescale. Chapter 5 presents the results of the field experiments at two scales; the Upper Derwent basin (15 Km²), and the southern Pennine region (2500 Km²).

In the Upper Derwent, total storm rainfall was often related to the general topography of the basin, but this was lost at shorter timescales, and when localised, convective processes were involved. At the regional scale, the occurrence of orographic rainfall patterns was much more obvious, especially for those rare cases with feeder-seeder mechanisms (i.e. no convective instability). For a basin the size of the Upper Derwent, it is suggested that as few as three gauges (distributed with altitude) would be adequate, even when convective raincells occur; the simple modelling exercise described in Chapter 7 suggests that hourly rainfall totals are a sufficient timescale for the Upper Derwent. There was an insufficiently large sample of storms to enable prediction of rainfall on the basis of synoptic conditions. However, the spatial pattern seems likely to be most predictable for 'pure' enhancement and least for thunderstorms, with convectionally-triggered raincells somewhere in between. Chapter 6 considers the accuracy of rainfall-radar over the study area and assesses its value for distributed rainfall-runoff modelling; if calibrated, the radar could prove extremely useful, especially in locating raincells at the regional and local scale.

It is concluded that "orographic" rainfall dominates the storm rainfall patterns of the southern Pennines. The Upper Derwent basin was too small to detect significant rainfall variation in terms of its effect on the storm hydrograph. Further work at the regional scale is required to confirm the predictability of rainfall distributions on the basis of meteorological conditions.

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1. Review of rainfall variation in time and space

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1.1 Review of rainfall inputs to runoff models

Runoff modelling has in the past emphasised catchment characteristics and paid relatively little attention to the quality and type of rainfall inputs. The development of runoff models from the black box approach to process-based models, accompanied by improvements in their efficiency in storm hydrograph prediction, has led to greater emphasis being placed on the quality and type of data input. In particular, the emphasis on (semi-) distributed catchment runoff models in recent years has emphasised the spatial variability of many of the input parameters (Beven and O'Connell, 1982; Beven, 1985). Linsley and Kohler (1951) were amongst the first to suggest that the typical rainfall input to runoff models could be one of the major sources of error and yet, very little research was undertaken until the late 1970's on the significance of this potential source of error. Roberts and Klingeman (1970) related rainfall parameters to hydrograph response using a laboratory model watershed. They found that rainfall intensity produced a marked difference in the magnitude of the hydrograph. Intensities of 0.131 and 0.155 inch/minutes produced similar shaped hydrographs, but lower intensities (0.112 inch/minute) produced a markedly different shape. This was attributed to the capacity of storage. The simulation of storms involving either upstream or downstream movement confirmed that its dominant influence was on the timing of the storm hydrograph. A storm moving up-basin produced an earlier rising limb, a broader crest and a more gradual recession limb than the down-basin storm.

The lack of attention paid to rainfall inputs to runoff models whether lumped or distributed is illustrated by a review of a number of typical models. Table 1.1 summarises the precipitation inputs.

Table 1.1
Rainfall Inputs to a selection of typical runoff models

Model Name	Type of Model	Catchment size	Time increments (input)	Rainfall Input	Reference
VSAS2	Distributed	59.64 acres	15 min. 1 hrly (rainfall)	1 hourly over area	Bernier (1982)
HEC1			mins-hrs	Basin weighted average	Thomas, W A (1977)
IEM4	Lumped		hrly	Hourly over entire basin	
SHE	Distributed				
Penn State Urban Runoff Model	Distributed			Each sub catchment weighting routine to preserve pattern (max. 30 subcatch- ments)	Aron & Lakatos (1981)
Moisture accounting watershed model	Semi-Distributed	delineated by isochrones	specified	Theissen polygons within zones (distribution)	Krzysztofowicz and Diskin (19)
TOPMODEL	Semi-Distributed	36 km		Lumped	Beven and Kirkby (1979)
WILSON MODEL				Theissen polygons (later modified to rectangles)	Wilson et al (1979)
HYMO	Distributed			Lumped	

- a) Topmodel is a physically based semi-distributed runoff model developed by Beven and Kirkby (1979) and initially calibrated for the Crimple Beck catchment (8 Km²). Subcatchments, topographically defined, are modelled separately using a lumped model. Rainfall is input as one value per time increment for the entire catchment. In a comparative trial Tagg (1982) calibrated the model for Hodge Beck, a 36 Km² catchment with a 300m height variation. The rainfall data was collected from a single autographic gauge outside the catchment and at a lower altitude. Yet, Tagg had noted that mean annual rainfall varied from 900 mm at 150m (OD) to 1000 mm at 450m. Although not a very large variation, on a storm basis it is likely there will be a varied spatial pattern. The simulated hydrographs under-predicted discharge for the summer months and over-predicted during the winter months. It was suggested that this could be due to the sub surface flow relation equations being incorrect. It is just as likely that the amount and distribution of basin rainfall was in error. For example, the autographic raingauge could be underestimating summer precipitation due to locally intense convective storm cells not being fully sampled. Although the model was designed to provide variable contributing areas, the major controlling input is seriously neglected.
- b) The Wilson model (Wilson et al, 1979) was initially developed to incorporate data from five autographic raingauges and mean rainfall calculated using the Thiessen polygon method. Later

'improvements' in the model allowed for twenty raingauges. The method of input preserved the 'essential features of the Theissen polygon method' but used 7.9 ml x 6.3 ml rectangles. The rainfall within each rectangle was then considered as uniform, again assuming linear and consistent variation in rainfall distribution regardless of topography. Whether the rectangles adequately portrayed the rainfall distribution within the experimental catchment or, the reasons behind the use of rectangles rather than some other shape, were not stated.

- c) A model paying greater attention to rainfall inputs in the Penn State Urban Runoff model (Aron and Lakatos, 1981). This is a distributed model designed to predict the quantity of storm water runoff. The catchment is divided into a maximum of 30 subcatchments by one of two methods based on segmentation of the natural or artificial drainage network. Rainfall can be input so that it varies both temporally and spatially. The weighting method employed to estimate rainfall from adjacent raingauges, is inversely proportional to the square of the distance between the raingauges and the subwatershed centroids. The attenuation of hyetographs resulting from weighting has been avoided by the allocation of a 'control' gauge to preserve the intensity/time relationships between adjacent gauges. This model appears to be one of the most comprehensive in its input and distribution of rainfall data.

1.2 Problems of rainfall measurement for runoff models

The paucity of distributed rainfall inputs to runoff models has been attributed to two problems; (i) that of sampling rainfall, and (ii) that of the sensitivity of models to the input (Beven and Hornberger, 1982). The sampling problem includes those of the density and distribution of the raingauge network and the incorporation of the data into the model e.g. calculation of basin/sub-basin mean rainfall. The second problem is predominantly of whether the current runoff models are sensitive to subtle variations in rainfall patterns and whether the simulated hydrograph response is physically realistic. Both the problems of sampling, and model sensitivity are considered below.

Estimating the rainfall distribution

The extent to which a raingauge network provides an adequate representation of rainfall in time and space is governed by the following major factors (O'Connell et al, 1978):

- a) type of rainfall;
- b) density and configuration of gauges in the network;
- c) the (time) resolution of the measuring equipment and procedure;
- d) how close the point measurements are to the rainfall at that point.

For areas with relatively level terrain, a uniform distribution of raingauges is likely to be the most accurate. The number of raingauges in the network will depend on the variability of precipitation in the area and the desired degree of accuracy in measurement (Corbett, 1967). Convective storms require a more dense network to attain the same level of accuracy compared to frontal storms characterised by large areas of more uniform rainfall. The sampling problem in mountainous areas is further complicated by the requirement of topographic parameters to be incorporated. Network designs in these areas theoretically tend to be irregularly spaced and more dense to include such influential characteristics as altitude, slope angle and aspect. Generalised guidelines are available advising minimum raingauge densities and network designs for different sized areas but on the whole, the only reliable method is to start with a very dense raingauge network and, after a period of years reduce the number by statistical correlation techniques (see O'Connell, 1978).

A further sampling problem is that of summarising the data for input to the runoff model. Under most circumstances this requires calculation of the basin or sub-basin mean rainfall for the time increment under investigation (15 minute to daily or weekly). This is basically a problem of extrapolating point rainfall distributions to areal distributions is therefore subject to the ability of the sampling network (gauge sites) to adequately portray the parent population (entire catchment) e.g. if all gauges are in valley bottom locations they may not adequately estimate plateau top rainfall. Many of the errors are however, lost in the computation of the areal mean

adjacent gauges with perpendicular bisects defining the boundaries. The area enclosed by the polygon is used to weight the rainfall amount at its central gauge. The basic assumption of this method is that rainfall varies linearly and uniformly between two adjacent raingauges regardless of terrain. It is thus highly inappropriate for mountainous terrain and yet, the most frequently used method of rainfall input for runoff models (e.g. Topmodel, Moisture Accounting, Watershed Model etc). One major advantage of this method is that gauges outside the catchment can be included.

d) Altitude weighted Thiessen Polygons

An adaptation of the previous method in which altitude is incorporated into the weighting factor. Altitude weighted Thiessen polygons suffer from the same disadvantages as the area weighted polygon method. Particularly time consuming is the problem that if one raingauge fails a whole new polygon network needs to be constructed.

e) Grouped area-aspect mean

This method is based on the assumption that altitude and aspect are important in controlling the receipt of rainfall. The catchment is divided into altitudinal zones and sub-divided by aspect. The sum of the area of each zone multiplied by the rainfall measured in each area, divided by the total area then produces the basin mean.

f) Triangular-area weighted mean

Nearby raingauge stations are joined to form triangles (eg vertices PQR). By measuring the length of the line joining two station (PQ) and the vertical distance (h) from the base to the remaining vertex, the mean rainfall over the triangle is:-

$$\frac{PQ (p + q + r)h}{6} \quad \text{where } p, q \text{ and } r \text{ is the rainfall at stations PQR}$$

g) Myers method

Whitmore (1961) describes this as a geometric method used to calculate mean weighted rainfall between pairs of stations, from which, in turn, average rainfall at the centroid of the catchment is calculated, weighted for the distance of those mean-value points from the centroid. A precipitation-elevation curve is compiled and the ratio between the rainfall corresponding to average catchment elevation and that corresponding to average station elevation is used to correct the average catchment rainfall for the effects of altitude. Only stations close to the basin centroid can be used and the technique works best for circular shaped catchments. This latter problem can be overcome by using more than one basin centroid.

h) Trend surface mean

Trend surfaces have been used by Dawdy and Langbein (1960) to calculate mean basin rainfall. The best fitting trend surface (orders 1 to 7) are fitted to the rainfall distribution. The mean rainfall is then calculated by the ratio of the area between 'isolines' multiplied by the rainfall total and used as weights in a similar fashion as Thiessen weights. This method seems to offer no great advantages over isolines drawn by computer or by hand other than the smoothing of irregularities.. No allowance can be made for topographic influences and 'irregularities' are smoothed on no hydrological basis.

i) Distance weighted mean

Gauges are weighted assuming that the differences in catch between two neighbouring raingauges is directly proportional to the distance between them (Goel and Aldabagh, 1979). It is a less subjective technique than the isoline method and more easily adaptable to computer calculation. It does not, however incorporate any topographic parameters other than distance between gauges.

j) Inverse squared distance method

This method involves the calculation of weighting factors inversely proportional to the square of the distances between raingauges and sub-watershed centroids (Aaron and Lakatos, 1981). Dean and Snyder (1977) recommend this method for consecutive hydrograph analysis because it preserves the temporal pattern of rainfall. This method is used in the Penn State Urban Runoff model.

Several authors (Whitmore et al, 1961; Mandeville and Rodda, 1970; Singh et al 1975; Aron et al, 1979) have made comparisons between the various methods of calculating mean basin rainfall. The more comprehensive study by Singh compared nine different methods in four different hydrologic environments and concluded that there was no basis to claim that one method was better than another. In fact, Singh refuted the claims of Mandeville and Rodda (1970) that complex trend surface analysis was preferable in the River Ray Catchment, GB. The choice of method is a qualitative one that depends on the quality of data available, the physiographic features of the area and the level of computational sophistication required.

The recent development of radar to measure rainfall obviates the problems of converting point rainfall to areal totals. Rainfall is estimated over 2 km or 5 km grid squares and all that is required is to grade the rainfall totals between adjacent grid squares.

Problems of Model Sensitivity

The second problem identified by Beven and Hornberger (1982) as influencing the quality of rainfall data input to runoff modelling

is model sensitivity. This is basically a problem of the development of the model and whether the simulated stream hydrograph reacts correctly to distributed rainfall inputs or whether it is lost in the computational runs. As already seen, those models purporting to be distributed still effectively have lumped rainfall inputs (Table 1.1). To what extent then, would more distributed inputs improve model performance? Bell (1972) using the Hacking River Distributed Model attempted to determine the impact of spatially varying rainfall. He concluded that the model was sensitive to temporal distribution of rainfall but not to variations in its spatial distributions. Higher rainfall totals in the lower catchment did however produce earlier flood peaks (and vice versa) by up to one hour. The Hacking River Catchment covers 15.4 ml² and was monitored with only six autographs, one of which was beyond the watershed. Unfortunately only two were used in the initial analysis, due to gauge failure, but it is highly likely that the complete network would have underestimated rainfall intensities because of small intense cells being missed in the coarse net. In addition, the catchment was divided at a midpoint so that rainfall variation could only be a two way division and not therefore convincingly distributed. Wilson et al (1979) using a deterministic rainfall runoff model and a stochastic rainfall generating model, threw dispersions on the frequently held belief that input errors would be damped out on routing through the model. The rainfall model generated the time distribution of rainfall depths at specified points within each storm in addition to storm duration. Wilson found that even when the total depth of rainfall was not in error, if the spatial distribution of rainfall is not preserved large discrepancies in volume may still occur. With a sample of fifteen

model runs, Wilson found a mean absolute error in peak discharge of 18% and a corresponding figure for time to peak of 13% (up to 40% on some occasions). As Wilson et al pointed out, rainfall was simulated for frontal type rain (e.g. long duration, low intensity) which is relatively predictable compared with isolated intense periods of rainfall moving randomly over the catchment.

Beven and Hornberger (1982) working on a much larger catchment (122 Km²) classified rainfall patterns according to the area of the catchment in which the higher rainfall totals occurred. As the sample size was not statistically reliable, stochastically generated rainfall was input to the distributed runoff model. The 1,000 thunderstorm type events generated broadly confirmed that found by Wilson et al. When the total rainfall volume remained constant, the rainfall pattern influenced the time to hydrograph peak as a result of routing through the channel network. Differences in the magnitude of the hydrograph could then result as a consequence of the coincidence of subcatchment hydrographs at the catchment outlet. This study dealt only with the storm totals and not with the movement of storms over the catchment. Both studies emphasised the importance of accurately estimating the total rainfall volume input. Similar results were noted by Hamlin (1973).

As noted by the authors, all these studies discussed above assume that there is no spatial variability in the catchment response or in the antecedent conditions. This would suggest the need for either more detailed simulation models or a calibrated distributed runoff model. Despite the apparent need as illustrated by simulated model runs and

discussed above, no studies have attempted to sample with a dense raingauge network specifically for runoff modelling. The problems of (1) how much actual variation there is, and (2) how important this is for influencing the stream hydrograph have not in fact been adequately determined using simulated or real data.

A case study to determine rainfall variability and its effects on observed runoff using a calibrated model is therefore of use in itself. Of more importance for general use is the prediction of rainfall variability given synoptic conditions, and the prediction of rainfall from a more limited gauge network. If dense raingauge networks were found to be essential for modelling purposes the cost both in maintenance and computational time would be prohibitive. If, given synoptic conditions, wind speed etc. in conjunction with topographic parameters the likely distribution could be predicted then the number of raingauges may be reduced to a minimum placed in carefully selected locations. Taking the step further, ultimately the calibration of radar may reduce the great emphasis currently on raingauges and improve the accessibility of spatially variable rainfall data. To conclude, it is evident that there is a need to firstly determine the significance and extent of the spatial variation in storm rainfall for input to distributed runoff models and secondly, to predict the rainfall pattern from a less dense raingauge network, using synoptic guidelines.

1.3 Nature and Causes of Variation in Rainfall

This section reviews the evidence to suggest that rainfall varies in its spatial distribution and in its time/intensity relationships on a

scale that may be important for runoff modelling. Two general approaches to the spatial variation of rainfall receipt are evident in the literature. Those concentrating on the meteorological aspects of precipitation and secondly, those relating rainfall to topographic parameters. Obviously, the two are closely interlinked but in the literature few studies bridge the gap.

i) Meteorological investigation of variability in rainfall receipt

Numerous authors have noted the cellular structure of rain cells within fronts and occlusions (Shearman, 1977; Osborn et al 1971). Their development and movement have further been identified by the use of rainfall radar monitoring (Browning et al, 1975). The mid 1970's saw the publication of several studies relating rainfall patterns to synoptic types. Atkinson and Smithson (1974) identified rain cells in occluding fronts on a mesoscale. Felgate and Read (1975) describe rain cells with sizes approximating 2.8 km x 1.3 km. Sharon (1972) noted cells of 5 Km radius, small enough to cover only part of a monitored catchment or move within it. Within these cells, which tend to move randomly over level terrain (Rainbird, 1975), the rainfall rate may be between two and ten times that in surrounding mesoscale areas (Austin and Houze, 1973). The occurrence and duration of these rain cells depends on the climate. Huff (1967) noted that 25% of storms in Illinois were composed of multicellular rainfall patterns and Rainbird (1975) cites their duration from a few minutes to an hour. The whole subject of the organisation and structure of precipitating cloud systems has been reviewed by Houze and Hobbs (1982).

One method of identifying these intense cells has been through the use of intergauge correlation techniques with near gauges being more strongly correlated than more distant gauges. These cells of more intense rainfall can locally cause large increases in rainfall totals compared to the wider area. A widely-spaced raingauge network could as a result easily underestimate total rainfall and under these conditions the radar coverage can be of most use. Intergauge correlation techniques have been widely used in the evaluation of raingauge networks and their uses reviewed by O'Connell (1978).

The importance of topography on the spatial variation in rainfall receipt has long been recognised but the processes involved have only recently been identified. Douglas and Glasspoole (1947) first doubted the widely held view that the increased rainfall rates over high ground were the result of the forced ascent of unstable air. The observed rainfall rates being too great to be accounted for by this process alone. Bergeron, in a series of papers from 1949, suggested the concept of "feeder" and "seeder" clouds to account for low-level enhancement of rainfall rates. High level seeder clouds, generated by frontal or topographic processes, provide raindrops which scour through low-level feeder clouds developed locally over the hills. Without this dual system, droplet growth would be too slow in the feeder clouds to account for the rainfall intensities observed.

Pedgeley (1970) confirmed the feeder-seeder hypothesis in Snowdonia and Hill et al (1981) using radar, in South Wales. This latter study identified the importance of the liquid water content of the feeder clouds and of their maintenance by strong low level winds, in

determining the variation in enhancement rates. From this study, they were able to identify three factors responsible for the intensity and pattern of orographic enhancement (Hill, 1981):

- a) the distribution of precipitation aloft (required to produce scouring of orographic cloud);
- b) relative humidity of air mass. Identified by the wind direction in the lowest 2 Km - maritime air has a high relative humidity than continental air;
- c) wind speed just above the friction layer. Strong winds maintain a larger supply of water vapour and cause a more rapid ascent of moist air than lighter winds.

From the experience of case studies in Snowdonia (Pedgeley, 1970) and S. Wales (Hill et al, 1981), Hill (1983) attempted to produce mean fields of enhancement over England and Wales for different wind directions, taking an upwind threshold of 0.05 mmh^{-1} . By studying days with frontal systems, in which relative humidity and rainfall rates are similar, the impact of different wind directions and speeds could be identified. Unfortunately, all the cases available had low level winds between SE and West. However, mean enhancement maps were produced (Fig 2.1) and other wind directions incorporated by comparison with the long term average annual enhancement.

Hill was able to confirm the concept of sheltering downward of high ground when wind backs from WSW to SSW. The resultant decrease in enhancement occurs over Exmoor, mid Wales and the Pennines. The average enhancement over the S. Pennines is less in the 55 kt than in the 40 kt wind groupings, for winds from the SSW sector. The opposite

conditions occur for other upland areas. Hill recognised the possibility of this being a statistical error by conjectured that it could be the effect of strong low level winds drying out over the long distance from Wales. Topographically, the optimum direction for enhancement over the S. Pennines is from the NE but the frequency of these winds renders then insignificant in the annual average enhancements.

The studies relating meteorological conditions to enhancement rates using radar suffers from several disadvantages. Firstly, all the detailed case studies have to date been at coastal locations where the topographic barrier is the first encountered by the air mass. This has enabled relatively less complex cases to be understood but invites the question: can these processes and thresholds be directly related to potentially more complex inland cases like the S Pennines? Secondly, these studies rely heavily on the radar adequately measuring rainfall rates over the hills. Most studies use only a limited number of raingauges with poor altitudinal distributions. For a more detailed understanding it is suggested that more attention should be paid to the ground pattern to confirm the accuracy of radar where ground clutter, re-evaporation and low level enhancement make calibration of the radar very difficult. The dense raingauge network installed for this project provides a good opportunity for testing the accuracy of the current radar calibrations in an orographic situation.

ii) Topographic investigations of variability in rainfall receipt

Numerous studies both statistically and empirically based have been undertaken relating rainfall totals to topographic parameters on a

range of spatial and temporal scales. Spreen (1947) was able to account for 30% of the variation in annual rainfall using elevation alone and 85% when slope, aspect, etc. were included. Burns (1953) confirmed these results using mean elevation with 8 km radius. Schermerhorn (1967) reported a high degree of explanation using an index of elevation rather than mean, or spot height. This incorporated a directional and distance weighting factor which enabled orientation of the mountain barrier in relation to air masses to be included. In the 1970's similar studies were undertaken in the UK. Chuan and Lockwood (1974) related annual and seasonal precipitation to mean relief within 8 km radius for the central Pennines. A higher level of explanation was achieved when the west and east Pennines were treated separately, the western side of the Pennines being more complex. On a smaller site than those studies mentioned above, Newson (1973) related rainfall to certain topographic parameters using the domain method (see section 3). This study, probably with the densest raingauge network, concluded that the dominant influence on rainfall receipt was elevation, with slope and aspect being only minor factors.

Although mainly on a storm total or larger time scale, these studies have highlighted the existence of spatially variable rainfall. Even in terms of the straightforward rainfall-elevation effect, it suggests a need to incorporate this pattern in rainfall-runoff models covering a wide range in relief. Within the Upper Derwent catchment instrumented for this study, the 300 m relative relief would add a further 561.1 mm LTAV rainfall to the highest area (calculated on Burt's (1980) long term average annual enhancement for the whole southern Pennines). This is based on altitude alone; when the effects of aspect and slope are

considered the pattern is likely to be complicated further. The temporal distribution of the enhancement is a further unknown - particularly the way in which enhancement depends upon synoptic conditions on this scale. This would thus suggest a need to measure enhancement rates on a within-storm basis for runoff modelling.

1.5 Aims

The major aims of this study are to:-

- 1) Determine the nature and extent of spatial variation in storm rainfall over a catchment. A storm is defined as a period of rainfall separated by any further rainfall by at least three hours of no rainfall, and with a storm total large enough to produce a storm hydrograph.
- 2) Determine the minimum variation of rainfall over the catchment which will have a discernable effect on the simulated storm hydrograph. Distributed rainfall-runoff models will be calibrated for the Upper Derwent catchment using both simulated and empirical data.
- 3) Identify the dominant controls on the observed rainfall distributions, in terms of meteorological parameters (wind speed, direction etc) and topographic parameters (aspect, altitude etc). This will then provide a basis from which to predict storm rainfall distributions.
- 4) In the light of these findings to define:-
 - a) the optimum raingauge network (number of gauges and location) for providing representative rainfall distributions for distributed runoff modelling.

- b) the level of definition in rainfall measurement and in its spatial expression required to improve the realistic routing of water through the catchment.
- c) assess the suitability of using radar estimates of rainfall for input to runoff models.

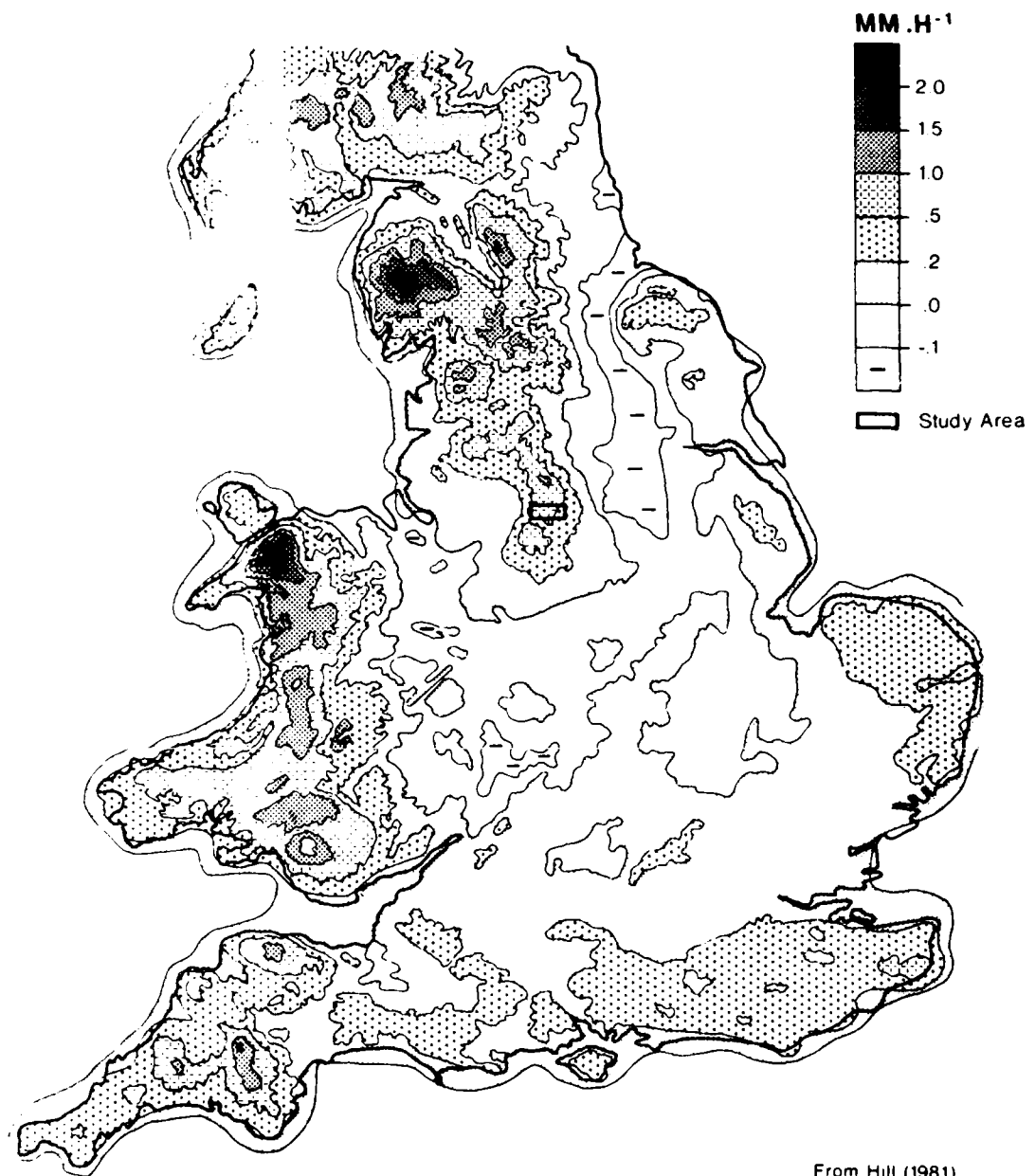
2. Choice of Field Site and Instrumentation

2.1 Choice of Field Site

To fulfil the stated aims of this project, the Upper Derwent Valley, Derbyshire (4160,3965) was instrumented. It possessed the following characteristics making it suitable for this study.

- 1) The relative relief of the catchment, ranging from 300-560m, and its position in relation to the Southern Pennine peaks would suggest orographic enhancement to be a factor determining rainfall distribution (see Fig 2.1).
- 2) On the catchment scale, the deeply incised valleys and flat plateau areas would offer potential for rainfall variation as a result of valley orientation.
- 3) The location of the catchment within an area of one of the densest autographic and manual raingauge networks in the UK, (see Fig 2.2) and its coverage by Hameldon Hill Radar, offer opportunities for relating the catchment scale rainfall pattern to the wider southern Pennines pattern.
- 4) The nature of the drainage network and the catchments rapid response to rainfall make it suitable for a rainfall-runoff model calibration. The 17 km² catchment outlet is instrumented with a broad crested weir owned by Seven Trent Water Authority. Past records and calibrations have been made available by the water authority.

Figure 2.1 AVERAGE ANNUAL ENHANCEMENT



From Hill (1981)

Figure 2.2

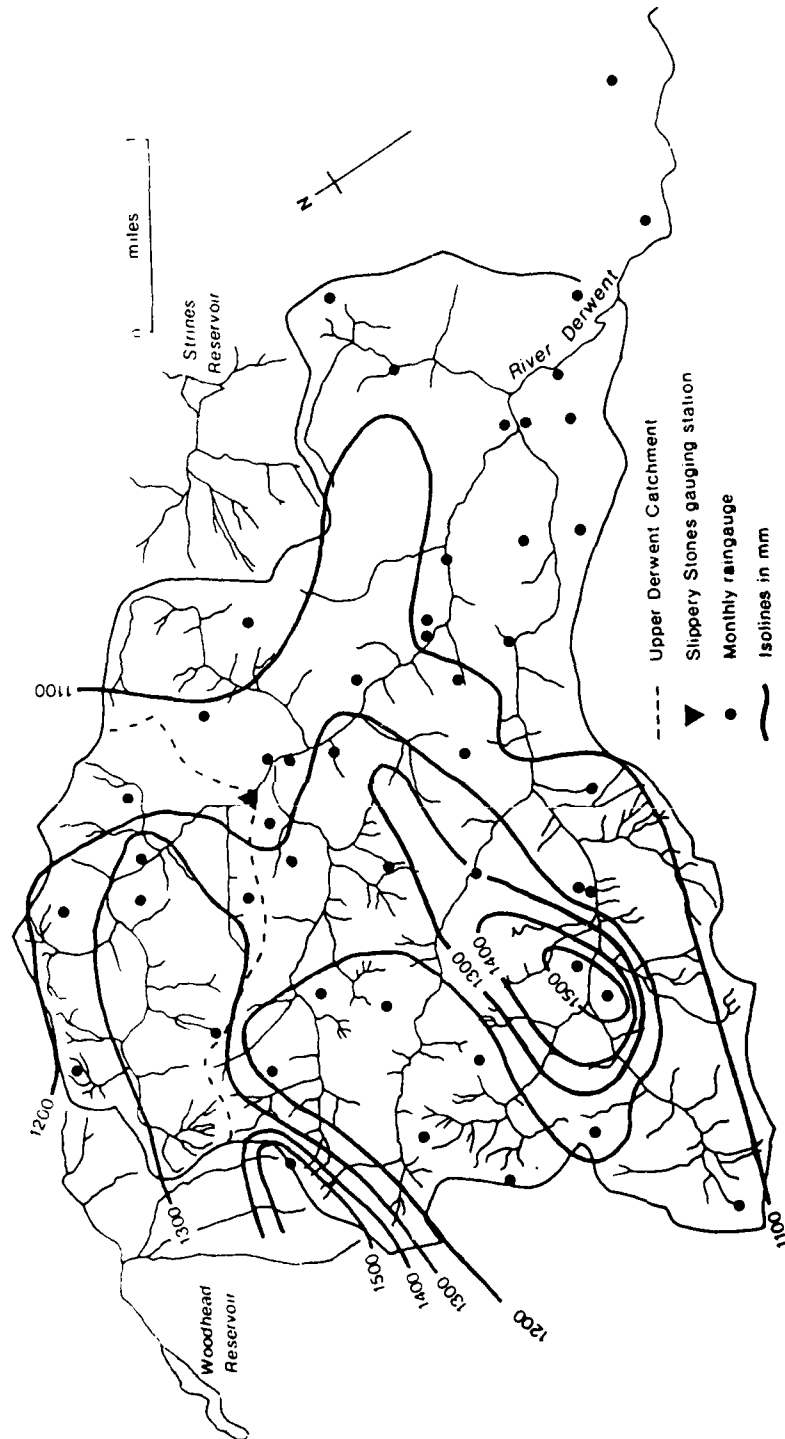
MEAN SPACING OF DAILY
READ STORAGE
RAINGAUGES, 1977 IN KMS



From O'Connell (1977)

The greater part of the Upper Derwent catchment consists of Kinder Scout grits of the Millstone grit series with smaller areas of shale-grits. The kinder grits form two distinct plateau levels (500m and 350m), the lower plateau being deeply incised. The plateau areas are covered by blanket peat up to 1.5 metres deep with varying degrees of erosion. On steep slopes and on much of the lower plateau the soils are very shallow sandy podsoils. The predominant vegetation types are Calluna, Eriophorum and Vaccinium with isolated areas of Molinia mainly in the south east corner of the catchment. The long term average rainfall (1916-1950) is 1270mm in the lower half of the catchment increasing to 1524mm in the north west half (British Rainfall Map, 1967). Sandeman (1916), maintained a dense network of monthly storage raingauges for the period 1900-1912. The 1900-1912 average annual rainfall ranged from 1200mm in the south east of the catchment to 1400mm in the north west (Fig 2.3). Sandeman did however note that many of the gauges were over exposed. Burt (1980), using multiple regression techniques produced a rainfall gradient for the Southern Pennines of 181mm per 100m rise. This could be broken down further to 120mm per 100m rise on the west slope and 202mm per 100m on the east slope. This would produce an annual total of 1322mm at the lowest part of the Upper Derwent catchment to 1828mm at the highest. Up to 1982, the Severn Trent Water Authority maintained several monthly storage gauges in the Derwent Valley. These studies illustrate the wide variation in rainfall receipt on an annual basis over the study area and its strong relationship with relief. No studies, to the authors knowledge have been undertaken on a shorter time scale.

Figure 2.3 Long Term Average Rainfall (1900-1912) For the Derwent Valley Watershed After Sandeman (1914)



2.2 Instrumentation

The field instrumentation consisted of a dense network of raingauges spread over the 17km² catchment. Recording raingauges were required for two reasons. Firstly, the timing of within-storm variation in rainfall intensity needed to be measured accurately through time; and, secondly, the topography and inaccessability of the site prevented the use of storage gauges emptied at short time intervals. A further specification of the raingauge network was that all gauges must be directly comparable. Any differences in either catch or timing, could then be attributed to real differences in rainfall receipt rather than to any of the numerous potential raingauge errors (see section 2.3.1). Therefore, attention has been paid to the methods of raingauge installation in order to eliminate or reduce to a minimum the possible errors in comparing raingauge catches.

2.2.1 Review of problems and methods of measuring rainfall

During the 100 years of rainfall measurement, the basic principle of measurement has remained the same (Rodda, 1967). The errors involved have been recognised but only solved or reduced to a limited degree. Developments in instrumentation have led on the whole, to measurements being precise rather than accurate (Davidson, 1978). With the exception of some research catchments, many of the errors have been 'overcome' by standardising measurements, usually at a compromise situation, rather than by refinement of the instruments. This is exemplified by the measurement of rainfall on a national scale. The Meteorological Office standards of gauges at 30.5cm high are adhered to and enable comparisons within Britain on the assumption that the errors are constant between gauges. Other countries have adopted different

height standards (on a similarly arbitrary basis) making direct comparisons between countries impossible. The World Meteorological Organisation (WMO) are carrying out a long term comparison of different gauge installations to produce a world standard. Countries with long term records using standardised gauge installations are naturally reluctant to change to a new standard.

The actual catch of a raingauge is a function of the true rainfall, the nature of the gauge and site characteristics, and the meteorological conditions pertaining (Rodda, 1971) (Fig 2.4). As a result, each gauge is characterised by different and varying sources of error. These errors can be divided into two categories, those attributable to the location of the gauge and those to the functioning of the gauge itself.

i) Location of the raingauge

Both the topography of the area (km scale) and the local site conditions (m scale) can influence gauge catch. The predominant and most variable error source being that caused by exposure to wind. Kurkyta (1953) estimated this error source to reduce catch by between 5 and 80%. The measurement error is caused by turbulence and increased wind speed in the vicinity of the gauge orifice resulting from the obstacle of the gauge in the wind stream (Larson and Peck, 1974). As air rises to pass the gauge precipitation which would have passed through the funnel is deflected and carried downwind and thereby reducing the catch (Chow 1968). Deficient catch caused in this way is particularly problematic both to estimate its size and to overcome because of its variability with both wind speed and rainfall intensity.

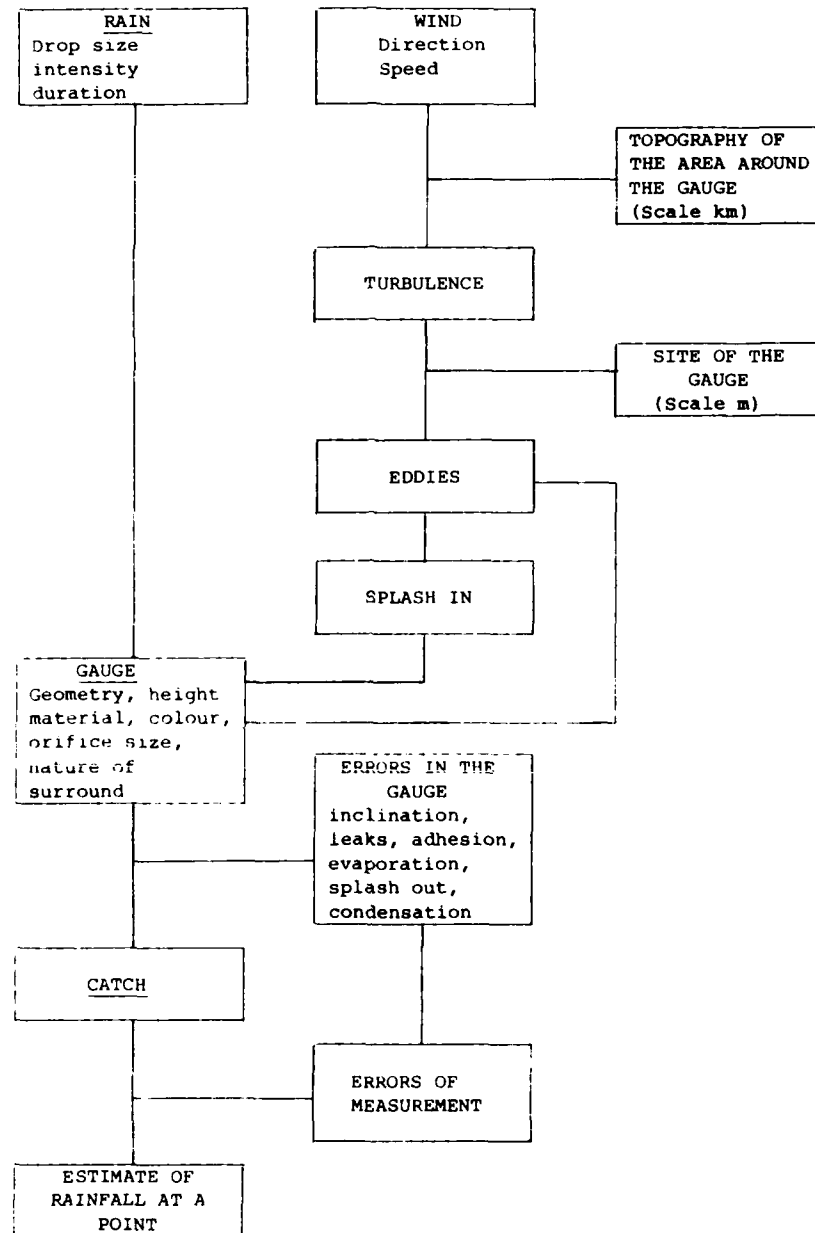
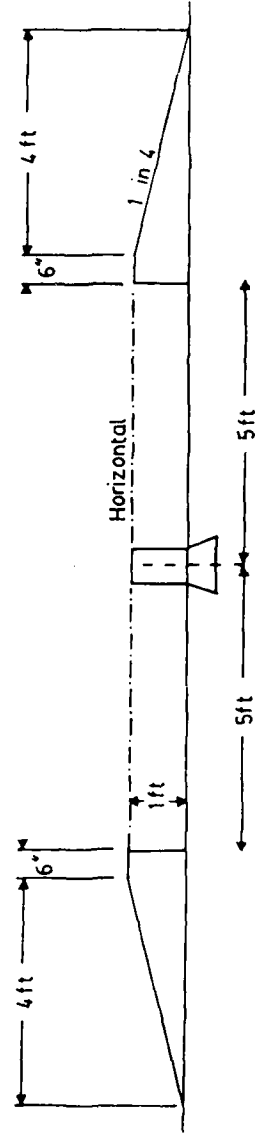


Fig 2.4 Conceptual model of the processes involved in determining rainfall with a conventional rain gauge.

FIG 2.5 TURE WALL FOR USE AT EXPOSED RAINGAUGE SITES



After:HMSO (1959)

Kodda (1963) found that the smaller water droplets trajectories are distorted the most and snow almost impossible to measure with conventional raingauges.

Elimination of the error usually involves modification of the wind field around the gauge either by judicious location of the gauge or modification of the gauge itself. However, the effectiveness of all the methods can only be established by either an increase in gauge catch or by comparison with ground "truth", ie. comparison to an unknown standard. The inherent danger then is that the increase in catch may not be wholly attributable to improved exposure but to some other factor most likely, splash in.

The Meteorological Office recommends the construction of a turf wall around a raingauge in an 'exposed' site, a method first used by Huddleston (1933). This consists of a wall with an internal diameter of 3m, height of 30.5cm and sloping outside wall of gradient 1 in 4 and crest of 15cm (HMSO, 1969; Fig 2.5). Alternatively, they suggest careful location of the gauge to avoid windy sites. Both methods are based on purely qualitative expressions of exposure and no guidelines are given for defining when a gauge is overexposed (Under exposure is prevented by the rule that no obstacles should be within two times their height away). Further, no measurements are made to determine the efficiency of the turf wall construction at individual sites and during different wind speeds, ie. it is possible that as wind speed increases they become less efficient in reducing exposure. The following statement by Larson and Peck (1974) typifies the qualitative approach given to this problem:

"for good exposure a gauge should have protection in all directions by objects of uniform height, the height of this protection varying from half the distance from the gauge to the protection up to a height approximately equal to the distance from the gauge to the protection. Care however must be taken to prevent over protecting the gauge."

A few attempts have been made at classifying gauges according to their exposure. Brown and Peck (1962) developed a classification of gauge exposure based on the degree of protection afforded by nearby objects and a knowledge of general terrain. Although a step in the right direction, the classification was wholly subjective. Lee (1972) recommended the use of the 'globescope', an optographic technique for evaluating the exposure of a raingauge. Although this gives an objective measure of exposure in terms of terrain it will still require relating to atmospheric conditions to be of direct use.

The use of shields around the raingauge orifice has long been advocated as a method of reducing the exposure error. These usually consist of a metal construction around the rim of the raingauge and functions by directing wind currents down and around the gauge thus reducing general tubulence and upward wind movement in the vicinity of the gauge orifice (Larson and Peck, 1974). A widely adopted shield is the Nipher shield (Nipher, 1978) consisting of an inverted cone; this functions by directing wind currents down and around the gauge thus reducing general tubulence and upward wind movement in the vicinity of the gauge orifice (Larson and Peck, 1974). A widely adopted shield is the Nipher shield (Nipher, 1878) consisting of an inverted cone; this functions poorly during snowfall. One shield that overcomes this problem is

the Alter Shield (Alter 1937). The performance of such shields vary with wind speed although it is generally more effective for snow than for rain. On the whole, they are not effective at wind speeds exceeding 20 mph (32 kph).

Modification of the gauge has also been attempted. Rotating and non-rotating vectropluviometers have been developed in an attempt to maximise gauge catch. Similarly, gauges with partitioned orifices have been developed (Green, 1976) but have not been widely utilised outside experimental catchments. Conover and Nastos (1981) advocated small orifice gauges because they minimised the obstruction, to the air flow and thereby reduced the exposure error. These are however only suitable for storm basis rather than weekly or monthly measurements.

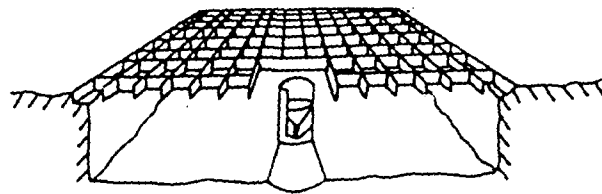
A few studies have looked at the aerodynamic shapes for raingauges (Robinson and Rodda, 1967) but no shape has been found that functions adequately for all feasible wind speeds and gusts.

The Meteorological Office standard of gauges at 30.5cm above ground level is a compromise between minimising splash-in from the ground and minimising the effect of high wind speeds over the orifice. However, there is evidence to suggest that the British standard is likely to suffer from both. Investigations have shown that splash from large diameter drops can reach a height of 600mm (Ashmore, 1934) and up to 1.2m has been recorded by Gold (1931) easily in excess of the 30.5cm stipulated by the Meteorological Office. The installation of raingauges at ground level, so that the gauge orifice is flush with the ground surface, obviates the problems of wind exposure but greatly

increases those caused by splash-in from the surrounding area. Numerous attempts have been made however to solve the problems by providing a splash-proof surface around the gauge (whose orifice is at ground level). Koschmeider (1934) developed the ground level gauge using brush matting and honeycomb grid to prevent splash, relating gauge catch to wind velocity and rainfall intensity (Winter and Stanhill, 1959). Reisbol (1934) comparing shielded and unshielded raingauges noted a considerable increase in catch by the pit gauge. Koschmieder (1934) recorded a 30% increase in pit gauge total and Hayes (1944), 50% with a sloped orifice pit gauge. The Plynlimon style gauge installation (Newson, 1977) allows the gauge orifice to be effectively 30.5cm above ground level (thereby preventing splash-in) but still out of the wind. This is achieved by placing the gauge in the centre of a pit 1m x 1m x 30.5cm with the gauge orifice flush with the ground surface (fig 2.6). An open pit would produce wind eddies affecting gauge catch so a honeycomb plastic grid is placed over the pit and level with the ground surface to simulate solid ground. In this way, there should be minimum disturbance to the local wind field and reduced splash-in. It should be noted however, that splash in still possible above 30.5cm (just as it is with the standard gauge). Robinson and Rodda (1969) found that gauges 30.5cm above ground level catch 6.6% less over a 5 year period than ground level gauges (Table 2.1).

To date the "Plynlimon pit" installation eliminates most sources of error present in traditional methods of raingauge installation. However, as it is not totally free from error it still cannot be said to catch what would actually have reached the ground had the instrument not been present.

FIG. 2.6 PLYNLIMON-STYLE ANTISPLASH GRID



ii) Errors attributable to the functioning of the gauge itself

Gauge catch errors attributable to the nature of the gauge are of two types. The first, are preventable as they are caused by poor gauge maintenance and gauge failure. These will not be considered here but over twenty-five possible errors have been detailed by Kelway (1975). The second, are a function of the way the gauge operates and includes wetting losses, condensation and splash out.

Wetting losses arise from evaporation of precipitation left in the container after measurement and adhesion of droplets on the funnel. Consequently, the rate of loss is dependent on rainfall intensity, wind speed and relative humidity. Gill (1960) evaluated daily evaporation losses from small orifice storage gauges (2.3 x 2.5" wedge gauge) which ranged from between 0.05 - 0.30". While Sevruk (1974) found evaporation losses amounted to 24% of yearly precipitation in a Hellmann gauge. Allerup and Madsen (1980) showed evaporation loss from a Snowden gauge at ground level only amounts to 1/5th of the loss from a Hellmann gauge at standard height.

Laboratory and field tests have been conducted to isolate the error attributable to wetting losses. Allerup and Madsen (1980) found that wetting losses amounted to 4% of annual precipitation with an average of 3% and 6% respectively occurring in winter and summer. While Sevruk (1974), found wetting losses amounted to 0.24% of total annual precipitation. Losses have been further broken down into losses from the collecting container and from the gauge funnel. The Snowden funnel produced losses of 0.1mm (Sevruk, 1974) and 0.09mm (Madsen and Allerup, 1980) during 1mm/hr rainfall event but was found in the field to be

Table 2.2
Differences in Rainfall Catch Between Ground-Level and Standard Gauges

Difference in Catch - Ground Level - Standard	Type of Standard Gauge	Period of Observation	Difference in Catch Calculated from following	Place of Observation	Author
1.0%	Israel 1m high	5 years	Average of annual totals	Negev, Israel	Stanhill, 1972
5.0%	MO Mk 2	1 year	Annual total	Wellesbourne, UK	Stanhill, 1958
5.7%	MO Mk 2	5 years	5 year totals	Chiltern hill top, UK	Green, 1970
5.76%	Specially constructed based on Mk 1A	8 months	Individual storms	Hill slope, Exeter, UK	Richardson, 1976
3.21%			Average of monthly totals		
5.4%	Israel 1m high	5 years	Average of annual totals	humid coastal plain, Lund, Israel	Stanhill, 1972
6.6%	MO Mk 2	5 years	5 year totals	Wallingford,	Rodda, 1967
7.0%	20.3cm dia. gauge at 30.5cm height	7 months	Average on monthly totals	Armidale, Australia	Jackson, 1974
24.0%	Standard gauge at 30.5cm height	14 months	14 month totals	Mt Cargill, New Zealand	Dreaver & Hutchinson 1974

(after Richardson, 1976)

related to rainfall intensity and duration. The Hellmann collecting container was found to lose 0.15mm (Sevruk) and 0.1mm (Allerup and Madsen, 1980) with similar finds for the Snowdon collecting container.

Wetting losses, adhesion and evaporation cannot as yet be eliminated but can be minimised by good raingauge design and maintenance and the use of narrow necked collecting containers. In the U.S.S.R. evaporation losses are corrected by the addition of 0.1mm to the catch total (Golubev, 1960) but this seems inappropriate because of the seasonality of evaporation losses.

A further source of measurement error arises where there is a difference in the angles at which the plane of the gauge orifice and a sloping ground surface intercept precipitation. The error becomes large when precipitation falls at an appreciable angle from vertical into a gauge with a horizontal orifice exposed on a steep slope (Helmers, 1954). Storey and Hamilton (1943) compared tilted and vertical gauges with a 10ft diameter control using slopes of 30-40%. Over 94 storms, the vertical gauge was deficient by 6.3% of the control gauge, the tilted gauge by only 1%. Aldridge (1976), comparing vertical with tilted ground level gauges on a daily basis found a relationship between the catch and rainfall inclination and wind run but no significant relationship between differences in catch and rainfall intensity. These studies highlight the need for tilted gauges on sloping ground. However, as Hayes (1944) points out a tilted gauge is no more effective than a vertical gauge in a well-sheltered location. Under these conditions the reduction of wind speed allows the raindrops to fall near to the vertical. For situations when good

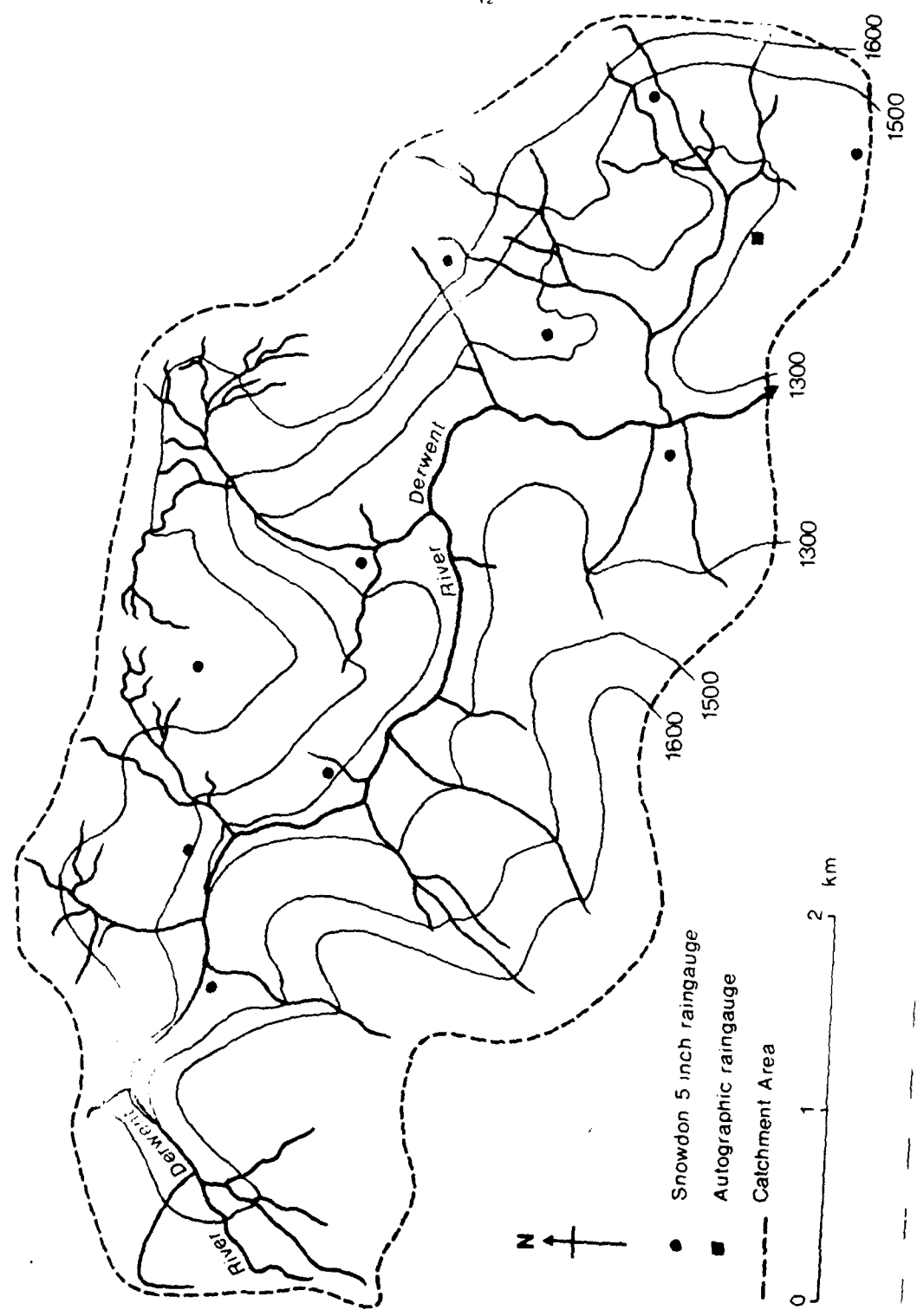
shelter is not available and gauges are vertical, Sharon (1980) has produced a computational model for correction. In this study, the adaptation of autographic raingauge funnels to individual slope angles was impractical. Fortunately, steep slope angles could be avoided and all gauges placed on either level plateaus or in positions where the local terrain is level.

To conclude, the accurate measurement of point rainfall is probably impossible because it is striving to an unknown goal or standard. The development of the pit gauge appears to offer the best solution to the major source of error, that of wind exposure, whilst good gauge maintenance will minimise the errors of evaporation, condensation and leakage.

2.2.2 Requirements for the Upper Derwent Catchment

The previous section emphasised the need for standardising the gauge exposure by some means (shields, walls or pit gauges) so that differences in catch could be attributable to real differences in ground receipt. A pilot study in the Upper Derwent catchment to determine the extent of rainfall variability over the area and to discover the problems likely to be experienced with running a raingauge network, was conducted from November 1982 for three months. Twelve Snowdon 5" manual raingauges were located within the catchment using a stratified random distribution based on altitudinal classes. The number of gauges in each band was related to the percentage of the catchment area within that altitude band, (see Table 2.2 and Fig 2.7). One Casella natural siphon autographic raingauge with a Snowdon check gauge was used to distribute the rainfall totals at the other sites through

Figure 2.7
DISTRIBUTION OF PILOT STUDY RAINGAUGES



time on a percentage basis (Clark et al, 1973). Only the autographic gauge was protected from wind exposure by the use of a small turf wall. No protection was given to the manual gauges as the construction of twelve comparable turf walls would have been too time consuming for a pilot study.

Despite the avoidance of very inaccessible gauge locations the network was still too large to cover in one day. This was the major problem in maintaining the network as it invariably rained overnight and hence added weight to the argument for a dense network of autographics rather than as the Plympton (19) approach of many manuals and distributing the catch through time using one central autographic gauge.

The pilot study was also invaluable in highlighting the following points:

- i) The gauges, wherever located, need identical exposure. Although large differences in catch were found, some of this was attributable to differences in exposure.

Table 2.2

Distribution of manual raingauges used in the pilot study

Height range (m)	% Catchment	Number of raingauges
305-396	18	2
396-457	32	4
457-488	15	2
488	38	4

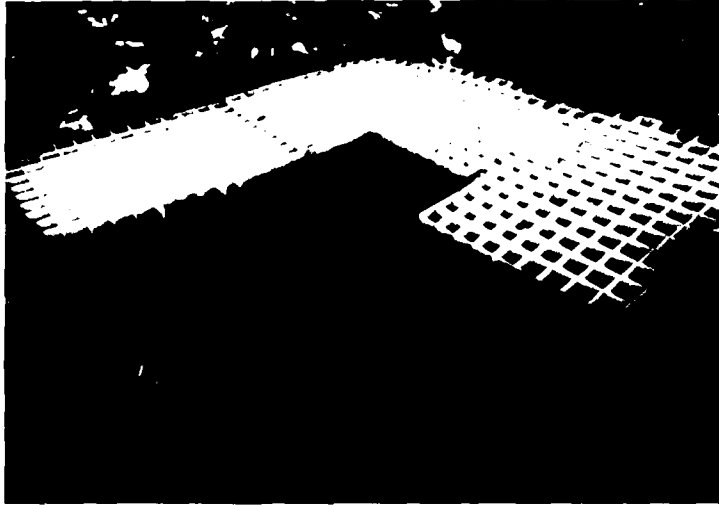
- ii) Gauges must be located far enough away from frequently used public footpaths to avoid theft and vandalism (one gauge was lost during the pilot study) and yet in accessible places to allow frequent maintenance.
- iii) Avoidance of areas with high water tables which prevented access to some sites or flooding of the gauge.
- iv) Gauges function poorly at low temperatures even with the addition of antifreeze and are useless during snowfall.

The requirements for instrumentation of the Upper Derwent then are as follows:-

- i) A sampling design of the catchment incorporating both a wide spatial coverage and a representative sample of the topography. (See Section 3.1).
- ii) Method of uniform gauge installation which provides identical exposure conditions with minimal environmental damage and visual intrusion. (The area is owned by the National Trust).
- iii) Autographic gauges to allow time and intensity to be recorded for individual storms.

The Meteorological Office solution to the installation of gauges in windy sites, as already stated, is to construct turf walls around the gauge. This method was not considered feasible for the Upper Derwent catchment because it would be almost impossible to ensure each turf wall had identical effects on the wind pattern and therefore equally efficient. Secondly, they would be visually intrusive. Rodda (1967) assumed that the Plynlimon pit installation was more precise with no absolute to compare with, but use of a pit would be beset with further

Figure 2.3 "Plimlinon Pit" reinforcement installation in deep peat.
The photograph shows the obvious problem of ponding
which occurs with any hole dug in deep peat.



problems in the Derwent catchment. The deep-water logged peats over most of the catchment precluded the digging of large pits as they quickly became water filled and the sides unstable. A trial run using turf walls and Plynlimon style pits at a site with similar hydrological conditions as Upper Derwent and nearer to the Polytechnic confirmed this, (see Fig 2.8). Minimum disturbance to both the peat and the natural vegetation was necessary to prevent ponding of water. The egg-crate louvres adopted by the IH were also prohibitively expensive.

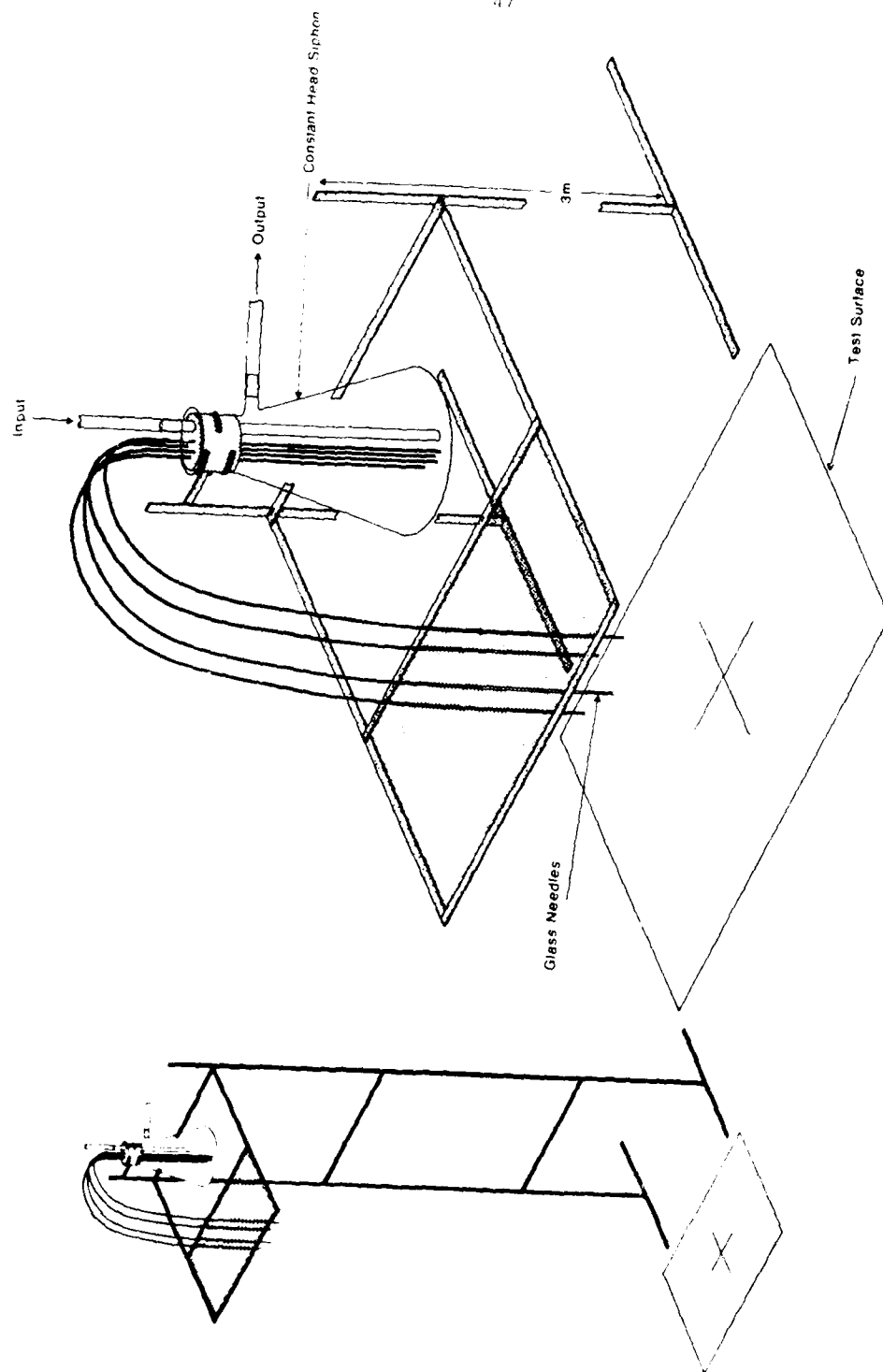
A method was needed that would enable the gauges to be buried at ground level (to standardise wind exposure) but in which splash-in would not be increased. Laboratory and field experiments were set up to find a surface that could be placed around the gauges which inhibited splash and cause minimum disturbance to the vegetation and peat.

2.2.3 Laboratory experiments of splash

The aim of these experiments was to identify materials that reduced splash and which could be used around the raingauges. Each surface was tested using a rainfall simulator and under both dry and water logged conditions.

The ability of a water droplet to splash is governed by its fall velocity which is, in turn, governed by its size ie. the terminal velocity increases as drop size increases (Hall, 1970). Unfortunately terminal velocity could not be attained in the laboratory for the full range of drop sizes likely to occur in natural rainfall. To simulate the range of drop sizes as closely as possible, a sprinkler system made

Figure 2.10 RAINFALL SIMULATOR



of extruded glass needles of varying diameters was raised to 3m (Fig 2.9). Under these conditions large drops could be produced which although they did not reach terminal velocity were approaching it; and the smaller drops may well have attained it. The rainfall simulator consisted of a plate of extruded glass needles each fed by plastic tubing from a constant head siphon. The rate of flow (rainfall intensity) was controlled by two Hoffman-type clips on each tube.

Both the height and horizontal distance of splash was considered important. The horizontal distance, because this would ultimately define the size of the antisplash surface and the height of splash, because this controls the vertical distance travelled and the effectiveness of horizontal winds in transporting the drops. To measure the horizontal distance, the test surface was surrounded by white cartridge paper and the water coloured with dye. Comparisons could then be made between test surfaces by using a fixed rainfall rate and range of needles for each test surface. The vertical height was measured in a similar fashion but with a cylinder of paper placed around the test surface. Surfaces tested included plastic grass, short grass, gravel, gravel and netting, bare soil, brush matting and angled louvres. All were tested under both free draining and water logged conditions.

No surface proved to be completely effective in preventing splash but, it did give an insight into the type of materials that are likely to be suitable under field conditions. These fell into two categories; those which deflected the water droplets away from the gauge orifice, and those which dissipated the droplets momentum. In doing this, the

now smaller drop sizes could not splash so high or as far. An attempt to test the various surfaces on water logged peat under similar environmental conditions as the Upper Derwent further emphasised the qualities required by the antisplash surfaces. Predominantly, that the surfaces should be permeable to allow the draining of surface water and secondly, minimum disturbance to the vegetation cover or peat surface.

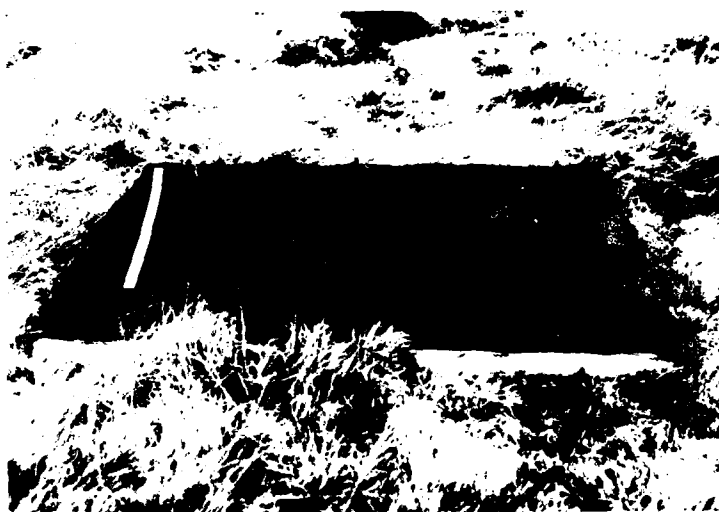
2.2.4 Field testing of splash surfaces

The materials used in the laboratory were also tested under field conditions at a site that was both easily accessible from Huddersfield, and with similar exposure to the Upper Derwent. Wessendon Head (NGR 4050, 4070) was initially chosen, being the same height as the Upper Derwent (460m) and with deep peat but, the very poor drainage precluded any data being collected with ground level gauges. Instead, a site at Hade Edge near Holmfirth (NGR 4135, 4045) was used; although the soils were more freely draining, the exposure and altitude were similar. A site was chosen with a shallow slope (5°) and unsheltered by trees or walls. Fifteen gauges were installed in an area of 0.5 ha. as below:

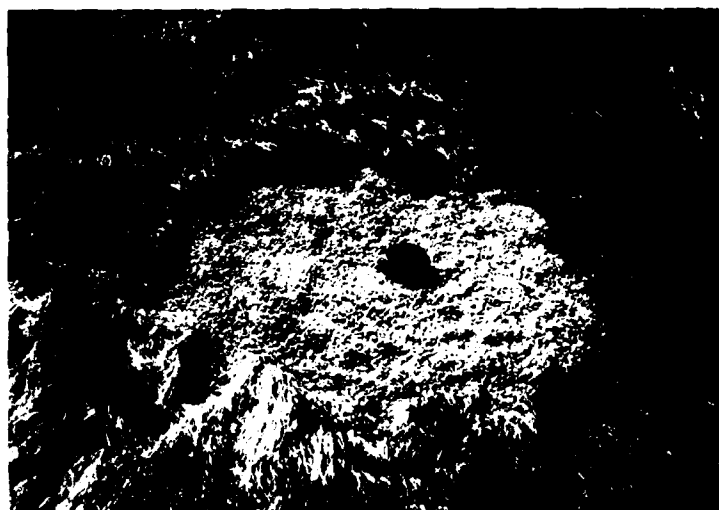
- i) Casella natural siphon autographic raingauge surrounded by a turf wall as to provide rainfall intensity and duration. The installation was at Meteorological Office specifications for a windy site (see section 2.2.1).
- ii) Four Snowdon 5" manual gauges at 30.5cm above ground level at the corners of the trial plot. This provided a measure of the natural random variability of rainfall across the trial plot.

Figure 2.10 A selection of anti-splash surfaces tested in the plot trials at Wade Edge near Huddersfield.

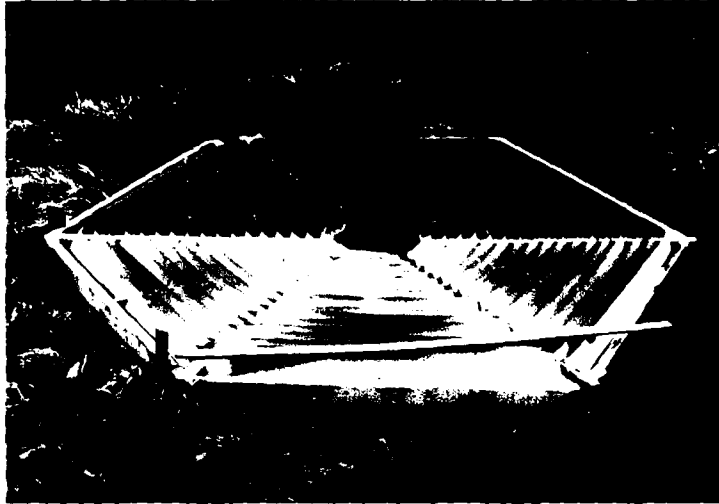
(a) Plastic net over grass



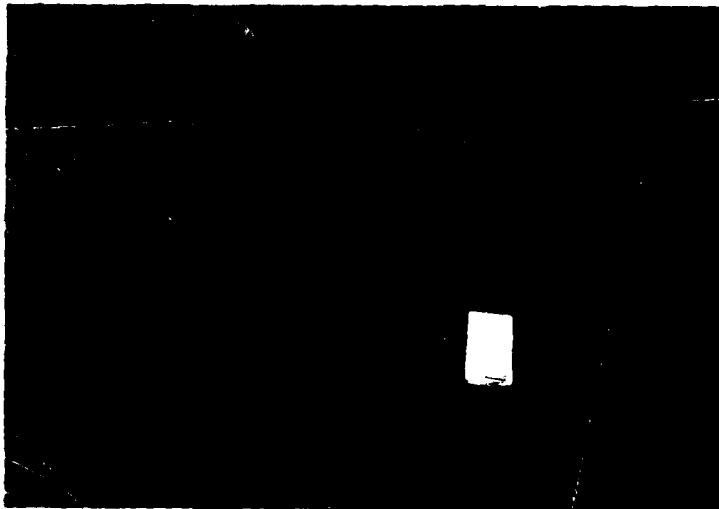
(b) Gravel



(c) Venetian Blind



(d) Plastic grass



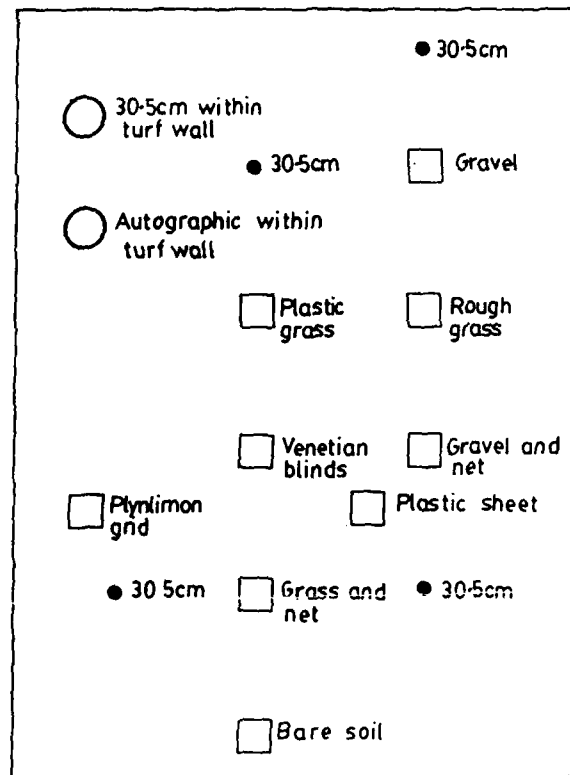
- iii) Snowdon 5" manual at 30.5cm surrounded by a turf wall. This provided a comparison with the plynlimon pit and the four manuals at 30.5cm.
- iv) Plynlimon pit. Snowdon 5" manual in a 1.3m^2 pit 30.5cm deep as specified by IH (Clark et al, 1973). This should catch the same at the manual surrounded by a turf wall.
- v) Snowdon 5" manual at ground level surrounded by rough cut grass.
- vi) Snowdon 5" manual surrounded by bare soil.
- vii) Snowdon 5" manual buried to rim and surrounded by $\frac{1}{4}$ " plastic greenhouse netting 2" above rough cut grass, (Fig 2.10a).
- viii) Netting over gravel. $\frac{1}{4}$ " plastic netting suspended 2" over $\frac{1}{4}$ " limestone chippings,
- ix) Gravel - 1m^2 of $\frac{1}{4}$ " limestone chippings, (Fig 2.10b).
- x) Venetian blinds. Metal Venetian blinds at an angle of 20° in an hexagonal frame, (see Fig 2.10c),
- xi) Plastic grass. 1m^2 of artificial grass, (Fig 2.10d).

Figure 2.11 shows plan view of the plot. Where possible all raingauges were emptied after each storm until thirty events had been collected. The storms were analysed for three characteristics:

i) Variation in rainfall over the plot

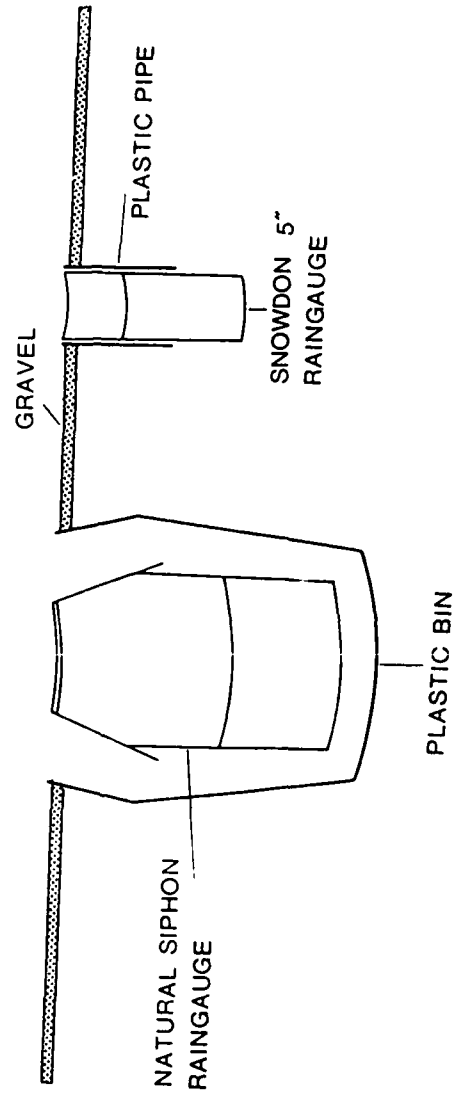
Any variation between the four manual raingauges installed at 30.5cm above ground level could be attributable to two causes; the natural random variability in rainfall receipt and secondly to measurement error. The latter was minimised by careful measurement and by emptying all gauges in random order so that no systematic error occurred. No gauges were emptied during precipitation because of the time taken

FIG 2.12 LAYOUT OF TRIAL PLOT



0 2
meters

FIG 2.13 RAINGAUGE INSTALLATION



gauges were emptied during precipitation because of the time taken to complete all the measurements. Over such a small area, it is unlikely that variations in exposure will be large enough to cause variation in gauge catch.

For twenty nine storm events, the average variation in totals between the manual gauge at 30.5cm is 8.68% of the average of the gauge catch. If however, the storms are divided into those where only three manuals at 30.5cm were available (17 storms) and those where all four were available (12 storms) the corresponding values are 10.95% and 5.46% respectively. The standard deviations about the mean are 7.16mm for all storm events, 8.3mm for events with three manuals and 2.91mm with four manuals. A correlation of 0.6 existed between average catch for the control gauges and maximum variation in catch, suggesting that the smaller the storm total the greater is the variation between gauges. This can probably be attributed to measurement losses. Very small amounts are easily lost though evaporation and on transfer from the collecting cylinder to the measurement flask.

ii) Comparison between Plynlimon pit installation, turf wall and over-exposed gauges

On a protected site, the catch of a gauge at 30.5cm, one in a pit and one enclosed by a turf wall to Meteorological Office recommendations (see section 1.21) should be identical. On an over-exposed site however, a raingauge at 30.5cm would be expected to catch less than the turf wall and pit installations. To test this hypothesis, the catch for thirty storms was compared between Snowdon 5" manuals installed in a Plynlimon pit, turf wall and unprotected.

For twenty nine storm totals, the frequency of overcatch, undercatch and identical catch compared with the Plynlimon installation was made, (see Table 2.3). The turf wall did not compare very favourably with the pit installation with different catches on 15 occasions (55% time). This can be attributed to the gauge still being over exposed despite the turf wall. This was anticipated as the wall had a smaller diameter than the Meteorological Office specification and is therefore unlikely to reduce higher wind speeds sufficiently. The performance of the gauge was however more similar to the pit gauge than the manuals at 30.5cm. For example, the turf wall installation caught identical amounts as the pit gauge on 13% of occasions compared with between 3.4% (manuals 2 and 3) and 6.9% occasions (manual 1). On over 80% of occasions, the manuals at 30.5cm were deficient in catch.

Table 2.3

Comparison between Plynlimon pit installation and
gauges installed at Meteorological Office Specifications

Gauge Installation	Frequency of over-catch (%)	Frequency of under-catch (%)	Frequency of identical catch (%)	No. of storms
Snowdon 5" @ 30.5cm	17.2	79.3	6.9	29
(2)	17.2	82.75	3.4	29
(3)	17.2	82.75	3.4	29
(4)	25.0	75.0	0.0	12
Turf wall	31.0	55.2	13.8	29

iii) Variations in gauge installations

The only method of measuring the contribution that splash-in is making to a raingauge total is by comparison to a ground control. As already stated, no method is yet available to measure accurately the actual amount of rainfall that would reach the ground had the raingauge not been present. The next best solution is to compare the catch with the most accurate method. On an exposed site this must be either the turf wall installation or pit installation. As the efficiency of the turf wall is dependent on wind speed and, there is evidence to suggest that the turf wall constructed on the plot was too small, comparison with this was not reliable. Instead, the Plynlimon pit method of installation was taken as the standard. All experimental gauge installations were compared with the corresponding pit gauge installation. Regression parameters and correlation coefficients were calculated between rainfall totals for each trial surface and totals for the Plynlimon style pit installation. The surface with the strongest correlation and a slope of unity would be the most similar in performance to the pit installation, (see Table 2.4 and 2.5).

The turf wall installation had a slope nearest to 1.0 (1.001) but had a slightly weaker correlation than the gravel installation; 0.996 compared to 0.999. The regression slope for the gravel was 0.997 suggesting undercatch on some occasions. This was however, the gauge corresponding most closely to the pit installation and was thus used to surround the ground level raingauge. It should be noted that the differences between many of the trial surfaces is very small and with the exception of plastic grass and polythene are all within 0.1% of the pit installation. The venetian blind trial surface was fourth equal

Table 2.4
Correlation between rainfall total for the Plynlimon pit gauge and
trial surfaces

Trial Surface	Correlation	Slope	Intercept	No. of storms
Manual 30.5(1)	0.999	1.019	0.09	29
Manual 30.5(2)	0.997	1.019	0.258	29
Manual 30.5(3)	0.999	1.055	-0.147	29
Manual 30.5(4)	0.999	1.036	-0.092	12
Turf Wall	0.996	1.001	-0.078	29
Bare Soil	0.998	0.983	0.231	29
Venetion Blind	0.999	1.017	-0.209	29
*Gravel Chippings	0.999	0.997	-0.067	28
Gravel and Net	0.995	0.975	-0.135	28
Net and Grass	0.999	0.995	-0.133	28
Artificial Grass	0.988	0.902	0.358	27
Grass	0.999	1.022	-0.111	29
Polythene	0.960	0.721	0.380	12

* Surface selected for field installations

Table 2.5

Comparison of trial surface raingauge catch with Plynlimon pit gauge

Test Surface	Frequency of over-catch (%)	Frequency of under-catch (%)	Frequency of identical catch (%)	No. of storms
5" manual 30.5cm (1)	17.2	79.3	6.9	29
(2)	17.2	82.75	3.4	29
(3)	17.2	82.75	3.4	29
(4)	25.0	75.0	0.0	12
Turf wall	31.0	55.2	13.8	29
Bare Soil	31.0	58.6	10.3	29
Venetion Blind	63.9	27.6	3.4	29
*Gravel	53.6	46.4	0	28
Gravel and Net	58.6	27.6	13.8	29
Net and Grass	71.4	17.8	10.7	28
Plastic Grass	71.4	17.8	10.7	28
Rough Grass	44.8	41.4	13.8	29

* Surface selected for field installations

but, was not suitable in the Upper Derwent: neither were grass or grass and net as there was wide variation in vegetation over the gauge sites. Most sites were on heather but some were an Empetrum or Molinia. This precluded the use of any antisplash surface that relied on natural vegetation cover. The positioning of the bare soil installation as fourth equal in performance was surprising in relation to that found by other authors (Ashmore, 1934, Green, 1976). This may be due to the relatively free draining nature of the upper soil horizons and the two nearby deep plough lines. Standing water was never observed around the gauge. On deep peat, which covers most of the Upper Derwent, this would not have been the case.

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2.3 Choice of instrument

The need for a large number of autographic raingauges and for inexpensive models severely restricted the choice of instruments available. Natural siphon raingauges were used in preference to 0.5mm tipping buckets attached to recording mechanisms for several reasons. Firstly, the mechanisms are very sensitive to movement so that with any peat instability the buckets would produce uneven tipping. Consequently frequent calibration would be necessary. Secondly the

time of the start of rainfall is impossible to determine given only the time of the first bucket tip. Finally, the most reliable recorders (solid state loggers) were prohibitively expensive to buy in large numbers. The major advantage of loggers, however, is that they provide very accurate real time measurement of rainfall. The loggers used within this study provided an excellent time basis and enabled chart recorders to be deciphered more easily. They were sited only on non-peat areas to reduced the chances of bucket movement.

Casella natural syphon autographic raingauges were chosen for the rest of the network as these were relatively inexpensive and light-weight compared to the Casella Dines or tilting syphon gauges. The gauges chosen work on a syphon mechanism which operates when the equivalent of 10mm of rainfall has occurred. A full description of the instrument can be found in Instruction Leaflet (3010/TN) from Casella (London) Ltd. However, these mechanical gauges proved unreliable for use at remote, inclement fieldsites.

Over the 1983 field season, 91 charts had a significant amount, or all, of the data lost. The average weekly failure rate was 28% or, a failure on average of 3.7 charts out of the 13 Casella autographics collected each week. The faults fell into four categories (Table 2.6):

- 1) Clock or clock gear failure: clock broken or gears too slack between clock and raingauge body.
- 2) Syphon failure:- this became the major problem with gauges failing to syphon their full capacity. This was normally a result of corrosion of the brass knife-edge over which the water is drawn down. A rough (dirty) surface of either the brass ring

or glass cover enabled air to escape and break the pressure difference. Weekly maintenance including shining the brass ring with 'Brasso' greatly reduced the incidence of syphon failure but by no means cured it.

- 3) Pen failure: inadequate leverage on the pen resulted in a faint or intermittent trace on the chart. This could quickly be alleviated by a lump of 'plasticine' on the counterweight end.
- 4) Others: these included damage to the float by ice, flooding as a consequence of exceptionally heavy storm in a dustbin with water already present.

Table 2.6

Causes of mechanical raingauge failure (Casella natural syphon gauges

	Total no. charts ruined	%
Clock and/or gears	48	52.7
Syphon failure	31	34.1
Pen	6	6.6
Others	6	6.6
	91	100%

Table 2.7 summarises gauge failure by week and location. It shows the difficulty of maintaining a large number of mechanical gauges in a harsh, remote environment. There is no guarantee that other mechanical designs would have performed any better on the Pennine uplands. By contrast, the tipping-bucket data loggers were almost totally reliable (apart from a problem of 'bouncing' buckets giving false tips, which was easily recognised in the computer output, and

Table 2.7

Causes of mechanical gauge failure by gauge and week

S - syphon failure; G - clock or gear failure; P - pen failure; n - gauge not operated
A3 and B5 are data loggers.

Gauge/week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	%
A1	S				G						P	P	P			P		G	n						n	S	S			71	
A2					G		S					G	G										S			G	n			79	
B4		S		G	G		S		S	G	G	G	G	n	G	G	G	G							n	S	n	S	G	59	
B6	S									G	G	G	S	P	n	P										P	n	G		65	
C7		S	G	P				S		S		S	n	n	G	G	G	G	S							G	S			58	
C8			P				S	S	G	G	G	G	P	n	n	S	G	G							n	n		G		58	
C9			S	S	S		S	G			S	S	n											n		n	G	n		73	
D10		G	G	G											n	n	S									G	G			78	
D11						G					G								S						G	n	n	n	S	81	
E12		S	G		P		S	S	S	S	n	n						S	n						n	G	G			62	
E13			S					G		S	P	n	n	G		S			n						S		G			71	
E14	S						S		S	S	n	n	n												S	n	S			77	
E15										G	n																G			93	
% complete record	85	67	77	38	77	100	67	92	61	69	85	77	15	42	80	86	69	78	92	61	69	92	57	100	69	89	64	16	38	77	

simply remedied in the field). With hindsight, the use of mechanical gauges at accessible sites only, plus purchase of more data loggers, would have been much more productive.

2.4 Conclusion

The results of the laboratory study and field experimentation showed limestone chippings to be the most effective in reducing splash around a ground level raingauge. This provided a means of installing both autographic and manual raingauges at ground level in the peat without having to dig large pits. The autographic raingauges were in plastic water-tight dustbins and secured by dexion frames so that the gauge orifice was at the same level as the rim of the dustbin. These were then buried so that the rim of the dustbin was 2.5 cm above the surface of the peat. The slightly higher rim prevented overland flow filling the dustbins and to allow for the gravel surround. The gravel was placed on plastic netting to prevent excessive loss into the peat and to ensure easy removal. Each ground level autographic raingauge was accompanied by a Snowden 5" manual checkgauge similarly installed to within 2.5cm of the ground surface and surrounded by gravel. The sides of the gauge were protected by plastic piping (Fig 2.12).

3. Network Design

3.1 Areal Sampling

Recording any spatial variation in storm rainfall distribution calls for the measurement of rainfall totals in both time and space. To monitor a number of storm events with a range of synoptic origins require measurement with a dense raingauge network over the catchment. The number of storms studied within each synoptic classification is dependent on the range of types occurring during the period of data collection (The majority of events will be collected from the period April to November 1983). Measuring over space can only be performed by a method of sampling that produces a 'representative' coverage of the catchment. The larger the sample size the more representation it will be of the parent population or, the more precise is the sample mean as an estimate of the population mean. Thus, two questions need to be answered. How many sample points (raingauges) are needed to produce the necessary accuracy of storm rainfall variation and secondly, where to locate the raingauges within the catchment.

The size and distribution of any sampling frame is dependent on:

- 1) the degree of variability in the parent population
- 2) the required accuracy of the 'analysis'
- 3) the subsequent statistical analysis to be undertaken
- 4) the feasibility constraints.

The nature of this study and the topography of the research catchment required the following points to be considered in the framework for data collection:

- 1) The cost of autographic raingauges and maintenance requirements restricted the number (sample size) to fifteen raingauges.
- 2) A wide spatial coverage of the 15 km² catchment was required to measure the variation in rainfall over the catchment for the distributed runoff input and for radar calibration.
- 3) To explain rainfall distribution from topography with a small number of sample points (raingauge sites) it is imperative to produce a network design that does not produce duplicate sites of similar topographic position, ie. to attain maximum efficiency from the sample sites.
- 4) Many studies have highlighted the significance of altitude in determining rainfall receipt. The framework, then, needs to incorporate altitude as a major consideration.
- 5) The sampling framework should incorporate a random element to allow other factors, not previously assumed as possibly influential on rainfall distribution, to be included in the design.

3.2 Review of sampling methods

Four types of sampling frame are widely used in geographical research and in particular for rainfall studies:

- i) The simple random sample enables each element in the population to have an equal chance of being selected and allows standardised statistics to be applied. Several authors (Wilm, 1943, Rycroft, 1949) have advocated this method for measuring rainfall variability with a small number of raingauges. A major disadvantage of this method is that there is no guarantee of

an even spatial coverage and some important elements of small areal extent can be missed (Dixon and Leach, 1977). Simple random sampling can thus be very wasteful of any prior knowledge of the parent population and is 'letting God dictate the experiment'.

- ii) Systematic point sampling enables a regular network of points to be selected and is most frequently used when an even coverage of an area is desirable (Dixon and Leach, 1977). The work of Linsley and Kohler (1951) illustrates this approach. A centrally located raingauges is surrounded by gauges at varying distances on the principal that as distance from the central gauge increases, on average, a less accurate estimate of areal mean is made. This network design should permit sampling errors to be smaller than a totally random design but is unsuitable for mountainous terrain. Although systematic point sampling is useful in the field, the sampling interval could pick up some periodicity in the population (Zarkovich, 1966).
- iii) Systematic random sampling is a compromise between (i) and (ii). The area under study is divided into units and a maximum number of randomly sampled points permitted in each unit. Any further points selected within the unit are rejected.
- iv) Stratified sampling involves dividing the area into units usually on some basis that is significant for the analysis and then picking points either randomly (stratified random) or at fixed intervals (systematic stratified). The stratified random method

enables known important elements to be incorporated, whilst allowing other unknown factors to be sampled. This method was used in the pilot study (section 2.3.2). The catchment was divided into five units by altitude (each band include ' 20% of the relative relief) on the basis of altitude being a major influence on rainfall receipt (see Chaun and Lockwood, 1974, Burt, 1980). A method of stratified random sampling was utilised for the Plynlimon raingauge network (Clark *et al*, 1973). Here, strata (domains) were delineated from 1:50,000 Hunting survey map on the basis of attitude, slope and aspect classes. All domains with an area exceeding 2% of the total catchment area had a raingauge randomly sited. Stratified random sampling can lead to an increase in precision which is effectively equivalent to an increase in sample size (Dixon and Leach, 1977) and was therefore desirable for this project.

3.3 Description of Computer Aided Experimental Design

The sampling framework chosen for this study was based on a stratified random sample which maximised the sampling of selected elements considered important (aspect, distance from high ground, etc) and minimised wastage by reducing duplication. The initial stratified random sample was optimised by Computer Aided Experimental Design (C.A.E.D), a package developed by I.C.I. Ltd (Goldsmith, 1981). C.A.E.D. is an interactive Fortran program available through Datacall Ltd on a time sharing system. The program operates on a repertoire of cells or sample points (potential raingauge sites) and their corresponding variables. The variables in this case are the attributes of each raingauge site considered as potentially influential on

rainfall receipt (eg. attitude, slope angle, aspect etc). The aim of the program is to select a sub-set of points in the repertoire which will maximise the amount of information about the variables as a whole. In order to judge the effectiveness of a subset, the program computes the determinant of the information matrix ($\det M$). If the choice of points is poor due to either high correlations between variables or, badly-spaced points, $\det M$ will be small. The program therefore seeks to choose the subset with the highest value of $\det M$ by taking a random selection of subsets, choosing the best one and then iteratively inserting and deleting points to increase $\det M$. The determinant is at its optimum value (1.0) when the values of the variables are at their most extreme limits. In reality, this is seldom achieved and in this instance, extreme values would be beyond the topographic features of the catchment ie. maximum slope angle and maximum altitude, taking only two, coinciding. The aim then is to strive towards unity and to achieve $\det M$ where the increase in value is progressively smaller as more cells (sites) are added. As well as listing $\det M$, the program also gives the maximum variance. The lack of information about the individual points in the repertoire is measured by the variance; the higher the variance the poorer the prediction of the rainfall pattern at a point. The program computes the variance at all the points and then prints the highest one as the maximum variance.

The package allows for numerous model designs but only the model used here will be discussed in detail. There are six major steps in the programme:

- i) specification of variables;
- ii) specification of repertoire;
- iii) specification of model;
- iv) size of experiment;
- v) computed design.

i) Specification of Variables

Each possible raingauge site can be characterised by its location and topographic features. Those considered as being important for influencing the rainfall pattern can be input to the model as variables. Up to twenty-six variables can be handled by the program and input as either quantitative variables or two level qualitative variables (0,1 or -1,+1).

ii) Specification of repertoire

The experimenter is required to input a repertoire of N feasible cells (ie. raingauge sites) which might be included in the final design and which are subsequently selected as subsets by random sorts. The larger the initial set, the more likely it is to be representative of the full range of characteristics in the parent population. In this instance, the larger the initial sample of points, the greater are the chances that it will have a similar range of characteristics as the 17 km² catchment. In this design, thirty sites were selected from which an optimum subset of fifteen was to be made.

iii) Specification of model

A choice is made between a model free design (non-parametric) or, as used here, a parametric model. A parametric model was chosen because

of the need to estimate parameters, that is, quantify the effect of variables on rainfall in the subsequent analysis. It is then necessary to specify which parameters are to be estimated. This could consist of linear terms (x_1 , x_2 , etc), quadratic terms (x_1^2 , x_2^2 etc) if a curved relationship between rainfall and a variable was needed, or product terms (x_1x_2 , x_1x_3 , etc) if the level of one variable affects the nature of a relationship between rainfall and another variable. In the chosen model, simple linear terms were always used (eg. $y = a + b_1x_1 + b_2x_2...$) and on some occasions square terms.

iv) Size of experiment

At this stage the experimenter is given the option of pre-specifying any of the repertoire cells which are to be forced into the final design. This option was used to prespecify two cells, one for each of the two data loggers. The computer then calculates how many different combinations of cells from the repertoire could be formed and predicts how long it would take to evaluate all of these (if all are evaluated this is termed a saturated design). If the predicted evaluation time exceeds 5 seconds (CPU) the user is required to put a cost limit (in pounds) on the computer time. The time limit restricts the number of random sorts generated and therefore the degree to which the subsequent design is near to the optimum.

v) Computed design

The computer design is tabulated so that the first column lists the serial number and the second the selected cell numbers with the prespecified cells first in ascending order. Columns three and four

lists two performance measures: Column three the value of the determinant of the information matrix, and column four the maximum variance. Finally, there is an option available for the printing of the correlation matrix for the final design.

3.4.1 Application of C.A.E.D. to the network design

The C.A.E.D. program offered the following advantages over conventional sampling procedures:

- i) A sample of points is chosen from the catchment from which C.A.E.D. select the optimum subset. In doing so, maximum efficiency can be obtained from a sample, an important consideration when sample size is small.
- ii) C.A.E.D. enables pre-specified sites to be incorporated into the design so that feasibility constraints can be included.
- iii) The method is very efficient in both operator time and computer time. Once the data for each sample point is stored, the specification of the model and run time can take as little as two minutes.

Choice of variables and repertoire:

i) Choice of variables

The selection of site characteristics input as 'independent' variables into the model was based on both past studies of rainfall variability and an attempt to get a representative coverage of the catchment. Initially thirteen variables were considered and measured from the OS 1:10000 series. However, because of strong auto-correlation between

many of the variables (Table 3.1) some had to be omitted. Two categories of variables can be identified; (a) those which provide a wide coverage of the catchment and; (b) those characterising the site topography.

- a) Northing and Easting were initially considered to provide a wide spatial coverage but, these correlated at 0.65. Easting was then substituted by distance west from the divide, which reduced the correlation between distance west and north to 0.03. Easting and distance west to divide correlated at 0.64. Distance to nearest gauge was considered as a means of ensuring good coverage of the catchment but, the nature of the programme in tending to select extreme values, would try to maximise the distance between gauges. Similarly, distance to Bleaklow was omitted because of its strong correlation with north (-0.64), east (0.99), maximum height within 2 km radius (-0.74) and distance west to divide (0.61).
- b) As already stated the need for a wide spatial coverage must be in conjunction with a representative coverage of the topographic character of the area. Hence, such parameters as slope angle, direction, spot altitude etc. which also influence rainfall catch, must be considered.

Several studies have shown how altitude has a dominant influence on rainfall receipt in the Southern Pennines. Spot heights could not be input in the model because extreme values tend to be selected. To overcome this problem, the catchment was divided on the basis of altitude into five areas of equal size (Table 3.2) using a hypsometric

Table 3.2
Correlation Matrix 13 Variables for the Thirty Proposed Sites

[illegible]

Table 3.2

Altitudinal division and polynomials fo the repertoire

Band Name	Altitude Range (m)	Area (Km ²)	% Catchment	Polynomial Variables			
				1	2	3	4
A	270 - 400 m	3.28	21.67	-2	2	-1	1
B	400 - 430 m	3.17	20.89	-1	-1	2	-4
C	430 - 470 m	2.94	19.38	0	-2	0	6
D	470 - 505 m	2.50	16.51	1	-1	-2	-4
E	505 - 595 m	3.27	21.55	2	2	1	1
			100%				

curve computed using the Apple microcomputer digitiser. 20% of the repertoire cells were located in each area. The five bands then needed labelling as dummy variables to facilitate each having an equal chance of selection. If labelled 1 to 5, the program would preferentially select bands 1 and 5. Similarly, if input as quadratics, bands 1, 3 and 5 would be selected. Instead, for dummy variables (always less than the number of bands), so coded that they are uncorrelated with each other were used. These are referred to as orthogonal polynomials. This method provided variables for each of the altitude bands (see Table 3.2). In the desire to optimise det M the program will choose a selection of points in the dummy variables which will correspond to 20% in each band.

Local topography was found, by Burns (1953), to be the dominant influence on gauge catch and thus must be incorporated into the network

design. Slope direction and slope angle were considered to be of particular importance. Slope direction was measured as predominant slope direction and input as sine and cosine. Slope angle was similarly measured from OS 1:10000 map as distance between two adjacent contours (contour interval 10m) and the cosine input as one variable.

On a larger scale, rainfall catch is likely to be influenced by adjacent high ground. To incorporate this, the distance to Bleaklow, the highest point (630m) just beyond the watershed, and distance west to the watershed divide were measured. It is likely however that high ground beyond the immediate catchment boundary may have an effect on the spatial distribution of rainfall. This has been incorporated as height and direction of highest ground within 1 Km radius. Table 3.3 summarises the variables considered and their method of input.

ii) Specification of repertoire

The model requires a repertoire of cells (possible gauge sites) from which subsets of fifteen sites are selected and compared. The larger the original sample size, the more representative the sample will be of the catchment. However, the calculation of the variables is time consuming and, beyond a certain point, the addition of more cells is unlikely to lead to a big improvement in the final design. Ideally the sites chosen should be selected totally randomly or by a recognised sampling frame (see section 3.1) to get a representative coverage of the catchment but the pilot study illustrated that certain areas were inappropriate for gauge installation. These were:

- 1) Near public footpaths.

Table 3.3
Final Choice of Variables

Variable	Method of Measurement and Input	No. of Variables
1. Northing	Three figure northing grid reference	1
2. Distance west to divide	Distance in Km due west to the watershed	1
3. Altitude	Catchment divided into five areas 20% by altitude. Five areas transformed into polynomials to allow equal chance of selection	4
4. Slope angle	Predominant slope angle (%) between two contours	1
5. Aspect	Predominant slope direction in degrees sine and cosine (+2)	2
6. Direction of highest ground within 2Km	Direction within 2Km radius as sine giving preference to east-west orientation	1
Total = 10		

All measurements taken from OS 1:10000.

- 2) On very steep slopes where natural syphon gauges could not be installed.
- 3) Areas of shallow peat or soil.
- 4) Areas prone to flooding or very high winter water tables.
- 5) Wooded areas.

In addition to these constraints, a network of gauges was required that could easily be maintained and serviced. It had to be possible to walk to half of the sites in one day so that consideration was also given to the accessibility of the site. Six gauge sites were randomly chosen in each 20% band of the catchment; those located in inappropriate places were omitted and replaced. Figure 3.1 shows the location of the thirty potential sites (cells) making up the model repertoire. For each of the 30 sites the 'independent' variables were calculated and then correlated with each other to minimise autocorrelation and therefore identify redundant variables. As already stated certain variables were omitted in the analysis for this reason.

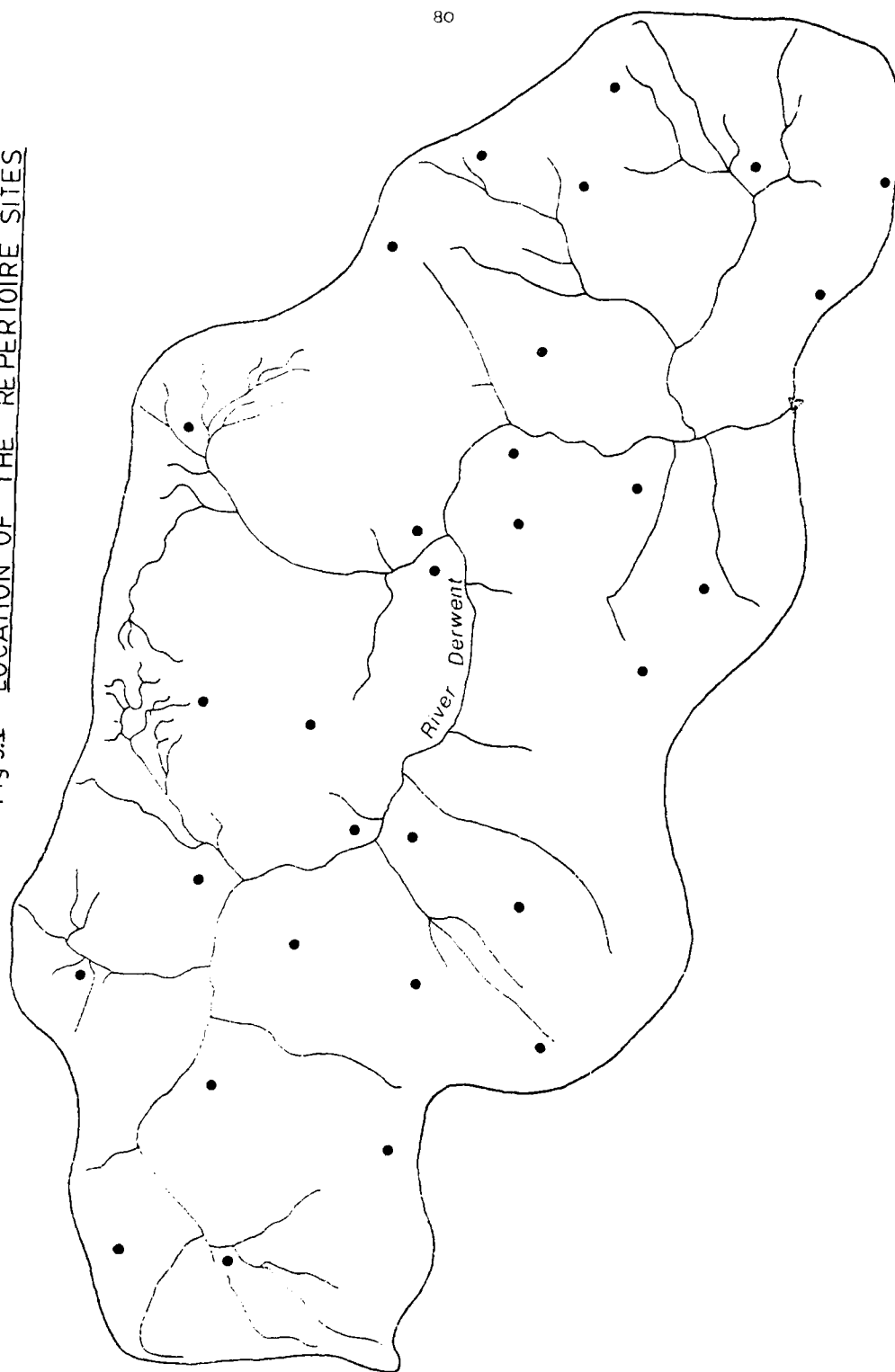
iii) Specification of the model

On all occasions, a parametric model was specified with simple linear terms in each variable. On some model runs, order two terms (squares) were specified in an attempt to force the choice of sites from central areas of the catchment. This is discussed further in section 3.3.1.

iv) Size of experiments

The size of the experiment was essentially dictated by the cost of equipment. Casella natural syphon raingauges were purchased as, being the cheapest they allowed a relatively large number to be bought.

Fig 3.1 LOCATION OF THE REPERTOIRE SITES



The fifteen raingauges (13 Casella natural syphons and 2 tipping buckets with data loggers) purchased, determined the size of the network.

3.4.2 Computer runs and selection of the final design

The model was run seven times, initially using northing, easting, altitude (four variables) and a constant term only (total seven variables). It was subsequently run with combinations of prespecified points, quadratics and all variables (total of ten variables). Two cells were prespecified as required sites for the two data logging raingauges. The aim of the data loggers was to provide a real time indication of rainfall events and thereby provide an accurate timing of storm cells moving across the catchment. It was thus desirable to have them as far apart within the catchment as possible and yet, easily accessible by land over so that 12v car batteries could be replaced. Cell 6 (151, 969) was the most northerly point in the catchment accessible by landrover with the added advantage of shallow peat and therefore improved drainage. The second data logger was located at cell 10 (174, 960) where the Severn Trent Automatic Weather Station (AWS) was to be installed at a later date. It was anticipated that the data logger could be installed here until the AWS was running and then moved to a more southerly location still within the catchment.

To summarise, a design was needed that would produce a reasonable spatial coverage of the catchment and minimise the correlations between the independent variables. These runs produced good coverage (two of them with quadratics to encourage selection of points in the middle

of the catchment). To distinguish between these, three points were considered in selection:

- i) The printed output on the design efficiency (maximum variance measure and determinant).
- ii) The coverage of the catchment by visual ordering by independent observers.
- iii) Nearest neighbour analysis of the point distribution.

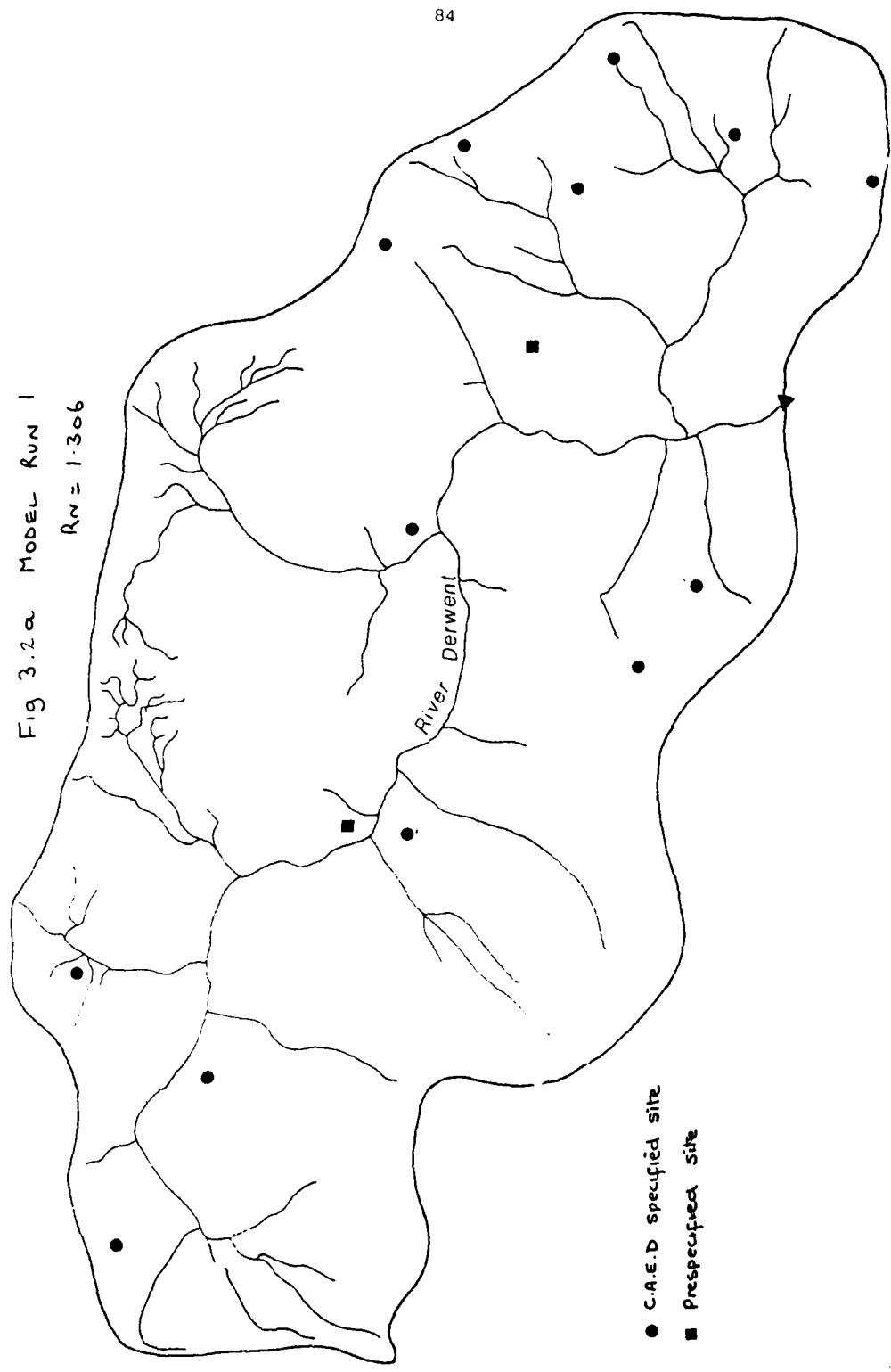
Nearest neighbour analysis is a method of assessing contrasts between actual patterns and their theoretical random counterparts. It is a three step procedure (Pinder and Witherick, 1972) in which the actual average distance between nearest neighbours is calculated and divided by the average distance expected if the points were randomly distributed. The problems of area boundry, size and shape, significant in areal comparisons, are not important in the use of the formulae here because all are held constant. The technique is used solely to give an idea of clustering rather than for inference. The resulting statistic (R_N) lies between 0.0 (completely clustered), and 2.15 (perfectly regular). A value of 1.0 indicates a random pattern. The R_N value for the thirty potential sites making up the repertoire is 1.57 indicating a tendency to regularity. The values for the seven model runs ranges from 1.306 to 1.662. An R_N value approaching 2.15 (perfect regularity) was required for a wide coverage of the catchment. Table 3.4 summarises the model runs, and Tables 3.5a-g give the detailed output for each of the seven runs. Figures 3.2a-g map the selected sites for each run.

fashion to the autographic raingauges. At site A3, the tipping bucket was attached to a Christie 12 channel logger, recording on magnetic tape and powered by a 12v car battery. The number of bucket tips in each 10 minute period is recorded on the tape which is subsequently read by a Christie Reader and stored on a PET floppy disc. Appendix A is a listing of a programme developed to convert the data into real time totals and intensities. The time period can be reduced at the expense of battery life and available tape. A ten minute period was chosen as this allowed both the battery and tape to last for the seven days between visits. At site B5, a P.D.L.5. solid state data logger has been installed. This records the time of each bucket tip to within one second onto a cachette. Cachettes are then sent to Data Research Services Ltd where data is translated into time of bucket tips, hourly intensities and rain day totals.

The data loggers provided a real time link across the catchment, with the data loggers beyond the catchment (see section 3.4.1) and, with the radar scans. It is desirable to have the data loggers as far apart within the catchment as possible and, as already stated, it is anticipated that B5 will be moved to B4 (181,943) when the Automatic Weather Station is installed at the former.

In addition to the autographic and manual raingauges at site A1, a manual raingauge at ground level and surrounded by a Plynlimon style screen has been installed. This is to provide a comparison between the pit gauge installation as used at the Plynlimon network and that used in this network.

Fig 3.2a Model Run 1
Rv = 1.306



- C.A.E.D specified site
- Prespecified site

Table 3.4
Summary of Model Runs

Run No.	Order 2 Terms	Excluded cells no.	Prespecified cells	R_N value	Distribution in alt band				
					1	2	3	4	5
1	-	15	6, 10	1.306	3	3	3	3	3
2	BB	-	6, 10	1.37	2	3	4	3	3
3	north & east ($r=0.64$)	15	6, 10	1.451	2	3	3	3	4
4	BB	15, 23	6, 10	1.535	2	4	2	3	4
5	BB	15, 23	6, 10, 4	1.537	3	2	3	3	4
6	BB	15, 23	6, 10, 21	1.475	3	2	3	3	4
7	-	15, 23	6, 10	1.662	3	3	3	2	4

The selected design (run 7) provided the best spatial coverage in conjunction with low variance (19.801) and high determinant (0.000015) compared to other model runs. Run 1 was the most effective of the model runs made with a higher determinant (0.000034) and lower maximum variance (17.801) than the chosen run. However, the distribution of sample points over the catchment was biased towards the south-east section of the catchment with few gauges in the west and north (Fig 3.3a). The nature of the investigation required a wide coverage of the catchment and so model run 7 with an R_N value = 1.662 was chosen in preference to model run 1 (R_N = 1.306). Unfortunately, the design chosen has an uneven distribution of raingauges with altitude (ie. only two in altitude band D and four in band E) but, this has no effect on the analysis as the bands were chosen only for the C.A.E.D. model and the model run chosen was the most efficient.

Table 3.5 (a)

RUN 1

Constant term: Y
 Order 1 terms: ALL
 Order 2 terms: NO

Total number of terms in model: 11

Number of prespecified cells: 2

Total number of combinations to be evaluated for a saturated design is 4686825 and this will require 127833 seconds of computer time. Thus, 36.7 random combinations can be calculated in one second and would cost 3.33p.

Number of evaluated combinations: 1102.

Computed design in sequential order

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	6		
2	10		
3	13		
4	14		
5	12		
6	19		
7	23		
8	2		
9	18		
10	26		
11	28	0.000014	31.677
12	11	0.000021	22.352
13	20	0.000025	21.669
14	29	0.000029	21.003
15	4	0.000034	17.801

Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12									
1	0.2035										
2	0.3848	-0.39									
3	0.2821	0.35	0.03								
4	0.1729	-0.16	-0.21	-0.32							
5	0.1211	0.00	-0.30	-0.27	0.12						
6	0.1634	-0.07	0.08	0.05	-0.06	0.04					
7	0.1834	0.27	0.08	-0.05	0.06	-0.08	-0.25				
8	0.3984	0.16	-0.24	-0.04	-0.03	0.19	0.33	-0.42			
9	0.1878	0.49	-0.16	0.19	-0.02	-0.07	-0.07	0.21	0.11		
10	0.2057	0.23	-0.05	-0.11	0.03	-0.16	-0.34	0.48	-0.39	0.10	
11	0.5044	0.70	0.43	-0.50	0.26	-0.02	0.06	0.10	-0.01	-0.32	0.04

Term Number	1	2	3	4	5	6	7	8	9	10
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Largest (Absolute) Correlation = -0.70 between Coefficients of Terms Nos. 1 and 11.

Fig 3.2 b MODEL RUN 2

$RN = 1.37$
(No high gauges on west side
of catchment)

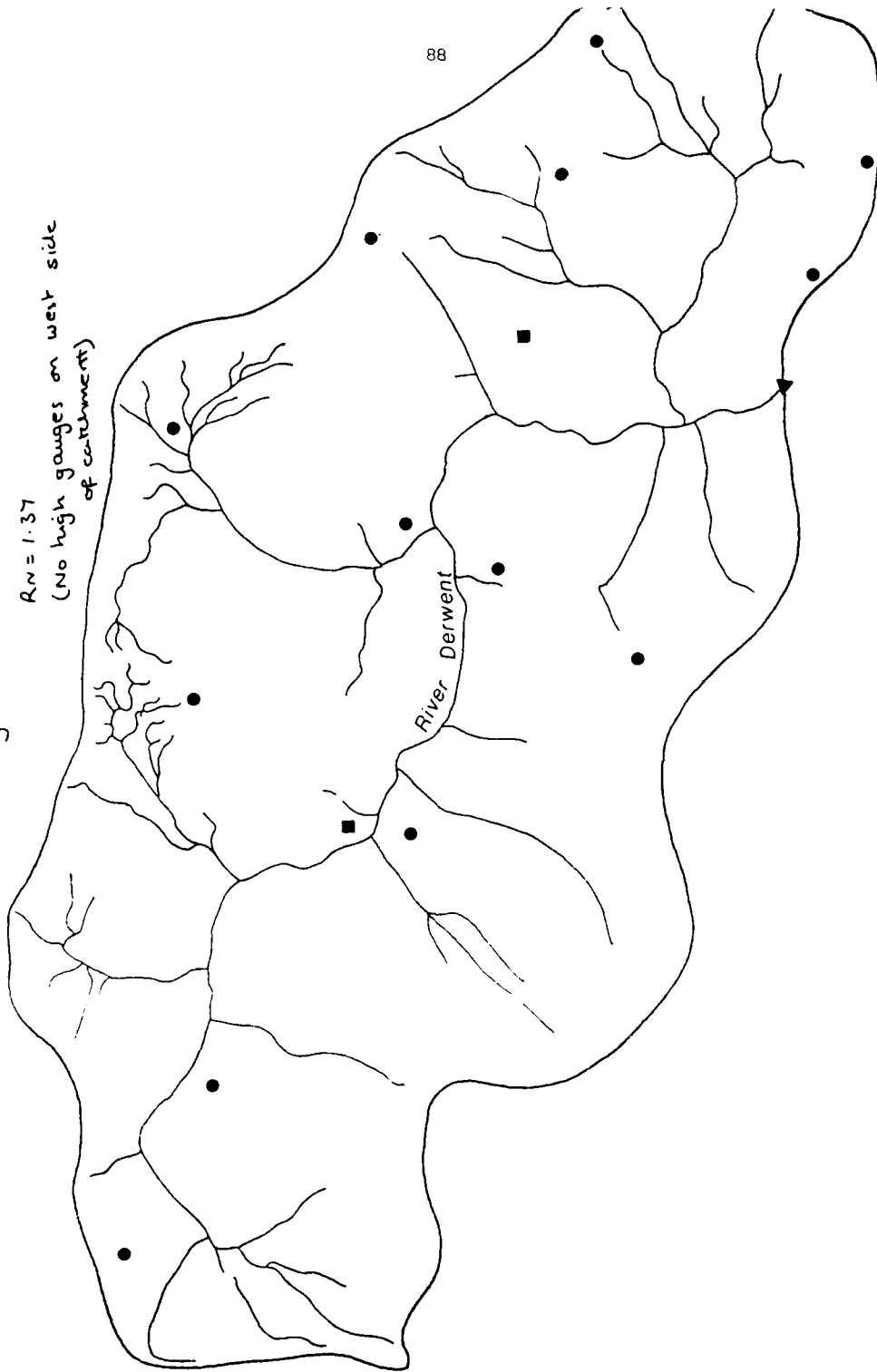


Table 3.5 (b)

MODEL RUN 2

Saturated design would require 13,123,110 combinations to be calculated which would require 440287 seconds of computer time.

Computed design in sequential order

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	6		
2	10		
3	26		
4	18		
5	20		
6	22		
7	23		
8	29		
9	12		
10	15		
11	13		
12	27	0.87E-06	37.565
13	2	0.14E-05	26.360
14	11	0.17E-05	22.790
15	17	0.20E-05	23.520

Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12										
1	0.4428											
2	0.5801	-0.61										
3	0.3200	0.17	-0.38									
4	0.3852	0.36	-0.16	-0.30								
5	0.1442	0.13	-0.40	0.02	-0.14							
6	0.1721	0.01	-0.02	0.18	0.09	-0.09						
7	0.1191	0.16	-0.17	0.12	0.07	0.16	0.01					
8	0.3276	0.47	-0.47	0.12	0.06	0.21	0.22	-0.02				
9	0.2040	0.46	-0.33	0.21	-0.00	0.11	-0.03	0.17	0.37			8
10	0.1457	0.08	0.13	0.07	0.11	-0.22	-0.07	0.02	0.14	0.01		
11	0.5967	-0.11	0.38	-0.62	0.54	-0.18	0.12	0.04	-0.11	-0.28	0.02	
12	1.5399	-0.70	-0.25	-0.14	-0.63	-0.16	-0.06	-0.08	-0.12	-0.11	-0.18	-0.44
Term Number		1	2	3	4	5	6	7	8	9	10	11

Largest (Absolute) Correlation = -0.70 between Coefficients of Terms Nos. 1 and 12.

Fig 3.2c Model Run 3
 $R_N = 1.451$
(Concentration in SE corner)

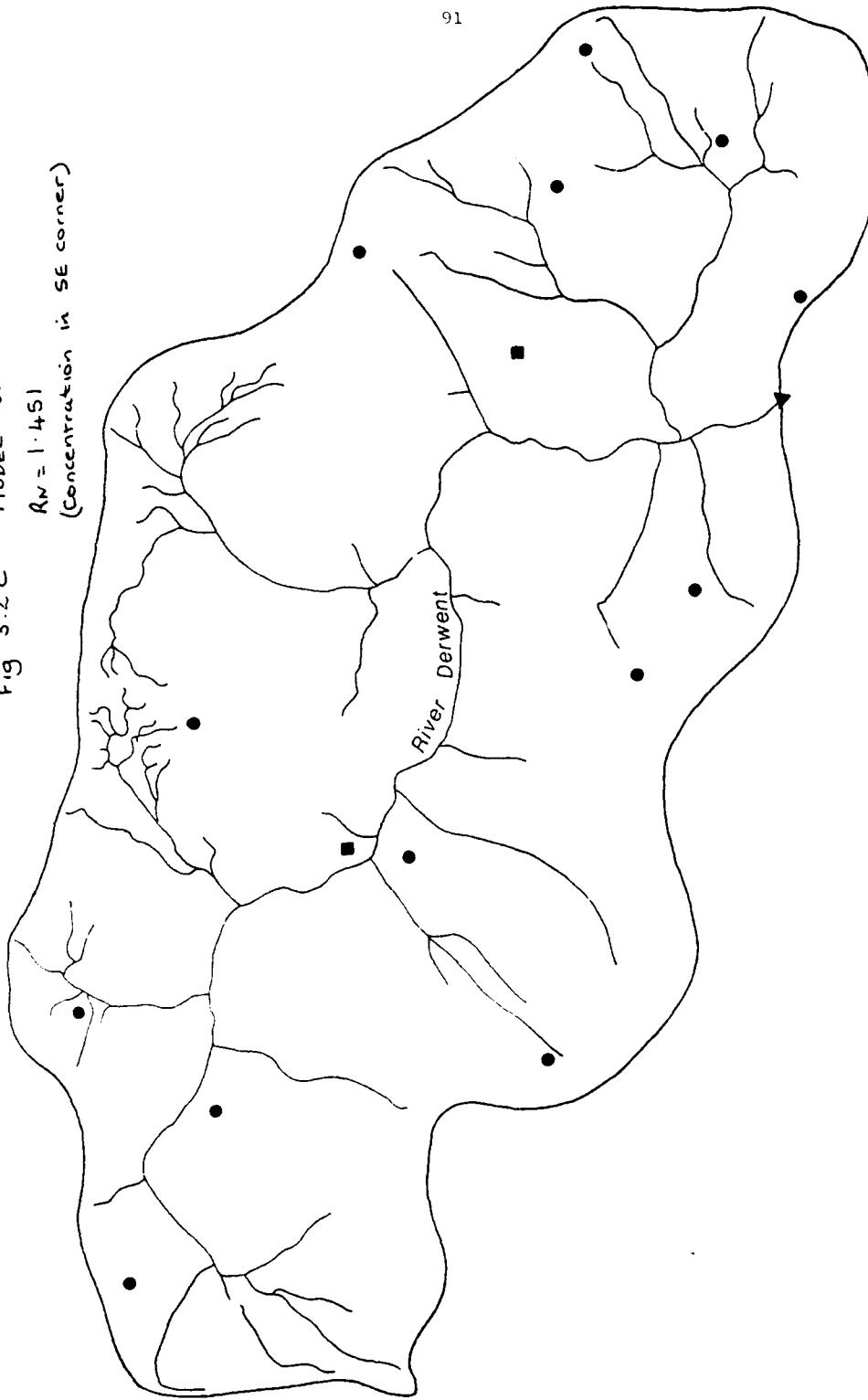


Table 3.5 (c)

MODEL RUN 3

Saturated design would require 8,436,285 combinations to be evaluated and this will require 283042 seconds of computer time.

Computed design in sequential order.

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	6		
2	10		
3	4		
4	20		
5	18		
6	22		
7	23		
8	14		
9	29		
10	30		
11	13		
12	11	0.37E-06	36.898
13	27	0.58E-06	37.543
14	26	0.93E-06	27.102
15	12	0.12E-05	22.396

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TOPOGRAPHIC CONTROLS ON RAINFALL AND RUNOFF(U)
HUDDERSFIELD POLYTECHNIC (UK) DEPT OF GEOGRAPHY
I P BURN ET AL. MAR 86 DAJ437-81-C-0019

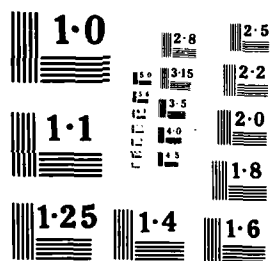
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Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12										
1	0.4946											
2	0.5154	-0.48										
3	0.2812	0.13	-0.40									
4	0.4754	0.57	-0.38	-0.17								
5	0.1556	-0.41	0.08	0.01	-0.38							
6	0.1971	0.09	-0.16	0.27	0.14	-0.01						
7	0.1770	0.27	-0.13	0.07	0.13	-0.22	-0.14					
8	0.4165	0.26	-0.41	0.18	0.17	0.11	0.42	-0.29				
9	0.2022	0.44	-0.38	0.19	0.23	-0.31	0.10	0.17	0.39			
10	0.2521	0.42	-0.20	-0.07	0.30	-0.42	-0.21	0.47	-0.24	0.21		
11	0.5701	0.16	0.45	0.63	0.31	0.04	0.02	0.00	0.16	-0.27	0.03	
12	1.7285	-0.79	0.25	0.17	-0.77	0.41	-0.10	-0.18	-0.05	-0.20	-0.36	

Fig 3.2.d MODEL RUN 4

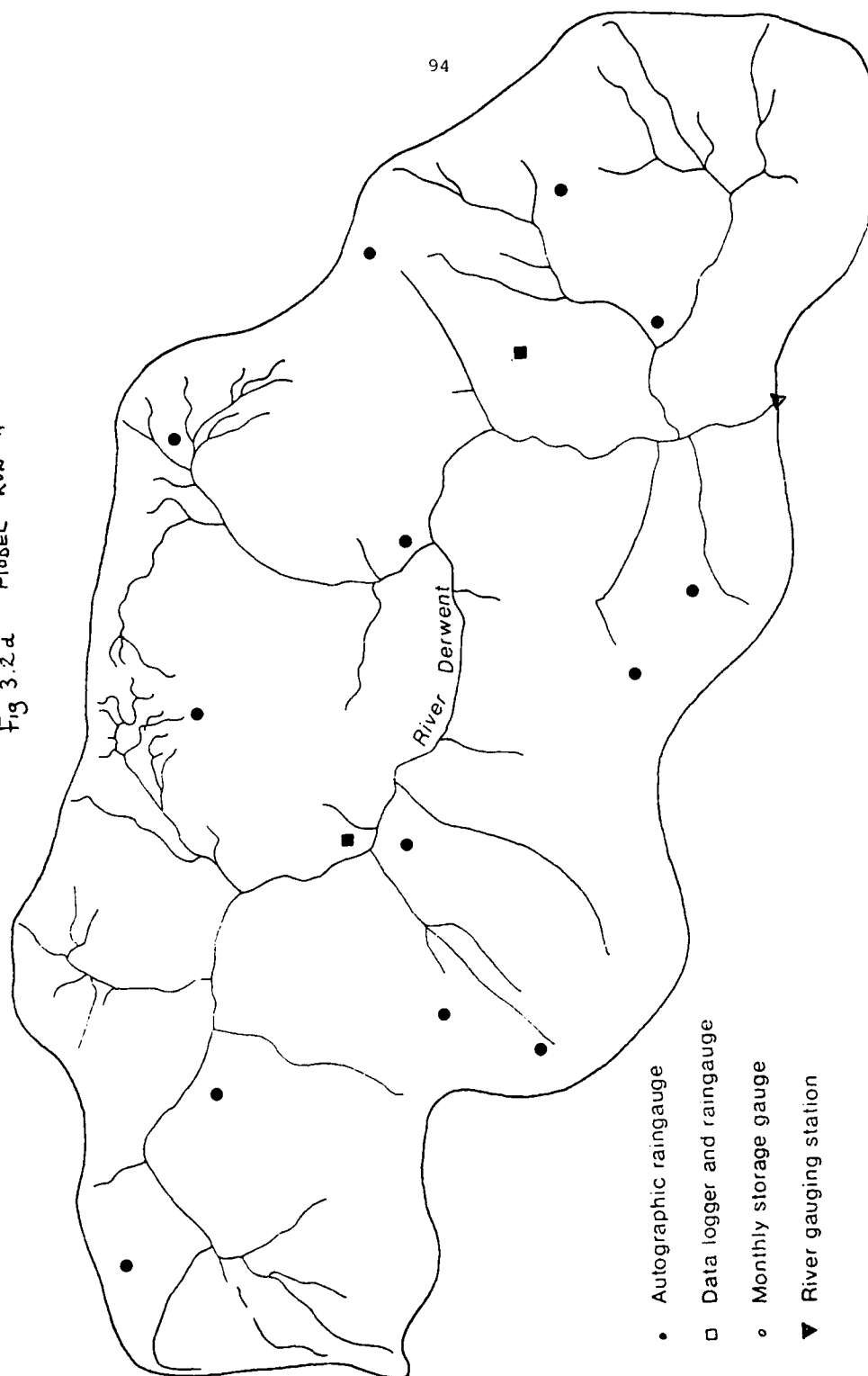


Table 3.5 (d)

MODEL RUN 4

A saturated model would require 5311735 combinations to be evaluated.
This would require 178212 seconds of computer time.

Computed design in sequential order.

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	6		
2	10		
3	4		
4	13		
5	14		
6	18		
7	20		
8	11		
9	22		
10	24		
11	27		
12	29	0.95E-07	43.696
13	30	0.17E-06	41.222
14	26	0.29E-06	31.980
15	2	0.42E-06	25.227

Fig 3.2e Model Run 5
 $R_w = 1.537$

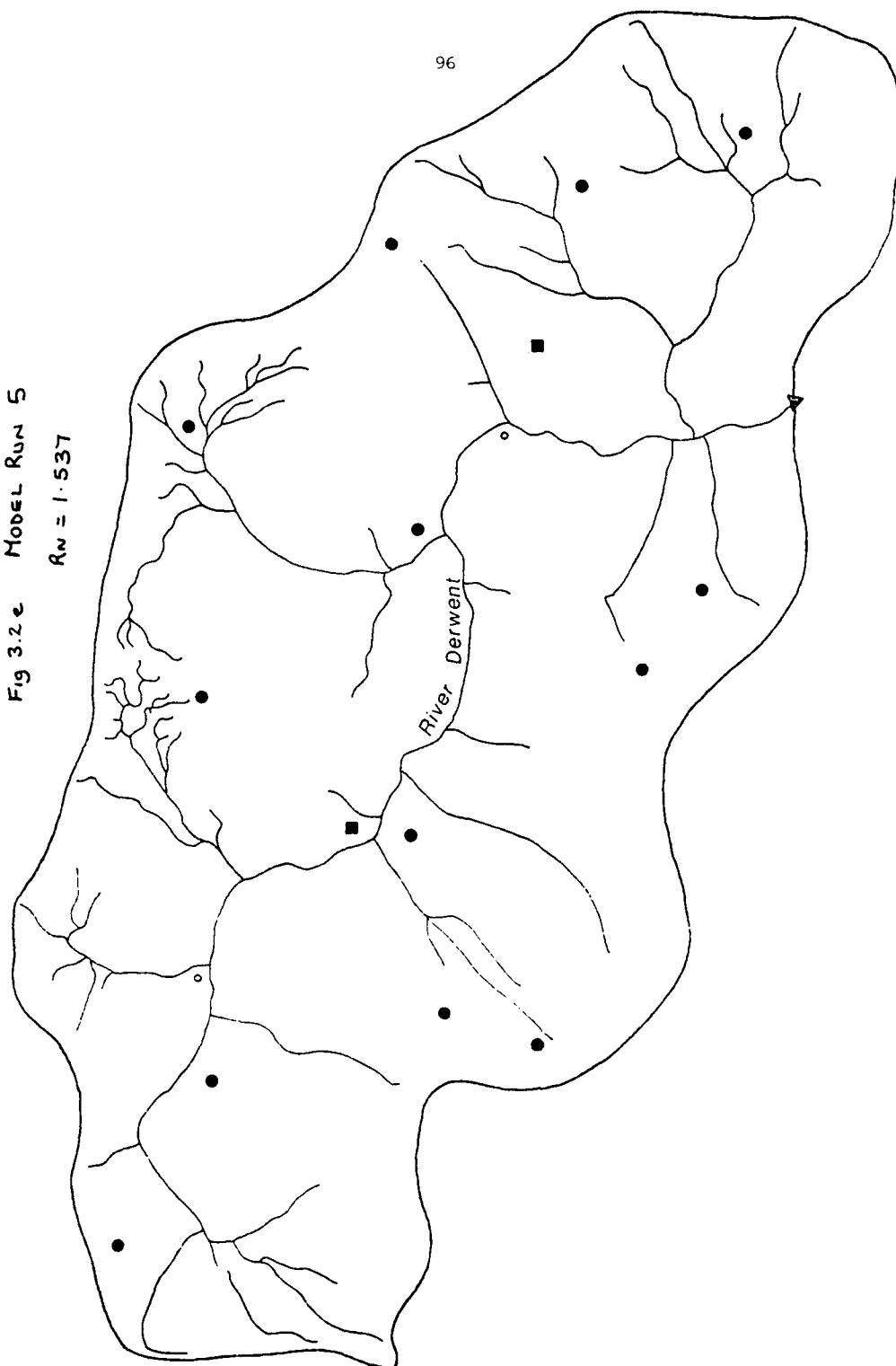


Table 3.5 (e)

MODEL RUN 5

A saturated model design would require 2042975 combinations to be evaluated. This would require 68543 seconds of computer time.

Computed design in sequential order.

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	4		
2	6		
3	10		
4	13		
5	14		
6	20		
7	18		
8	22		
9	24		
10	27		
11	29		
12	11	0.95E-07	43.696
13	30	0.17E-05	41.222
14	26	0.29E-06	31.980
15	2	0.42E-06	25.227

Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12										
1	0.4700	-0.43										
2	0.7332	0.20	-0.49									
3	0.3402	0.54	0.30	0.08								
4	0.4278	-0.25	-0.22	0.14	-0.18							
5	0.1255	0.02	-0.16	0.06	-0.07	0.04						
6	0.2247	0.10	0.30	-0.14	-0.02	-0.26	-0.32					
7	0.2394	0.30	0.66	0.40	0.23	0.30	0.31	-0.56				
8	0.8853	0.29	-0.24	0.10	-0.01	-0.10	0.32	0.06	0.23			
9	0.1730	0.38	-0.13	0.03	0.27	0.26	0.39	0.32	0.07	0.03		
10	0.2504	-0.05	0.24	-0.61	0.46	-0.13	0.04	-0.05	-0.01	-0.05	0.06	
11	0.4995	-0.70	-0.04	0.27	-0.67	0.38	0.07	-0.24	0.16	-0.09	-0.24	-0.35
12	1.6804											
Term Number		1	2	3	4	5	6	7	8	9	10	11

Largest (Absolute) Correlation = -0.70 between Coefficients of Terms Nos. 1 and 12.

Fig. 3.2.4
MODEL RUN 6
 $R_w = 1.475$

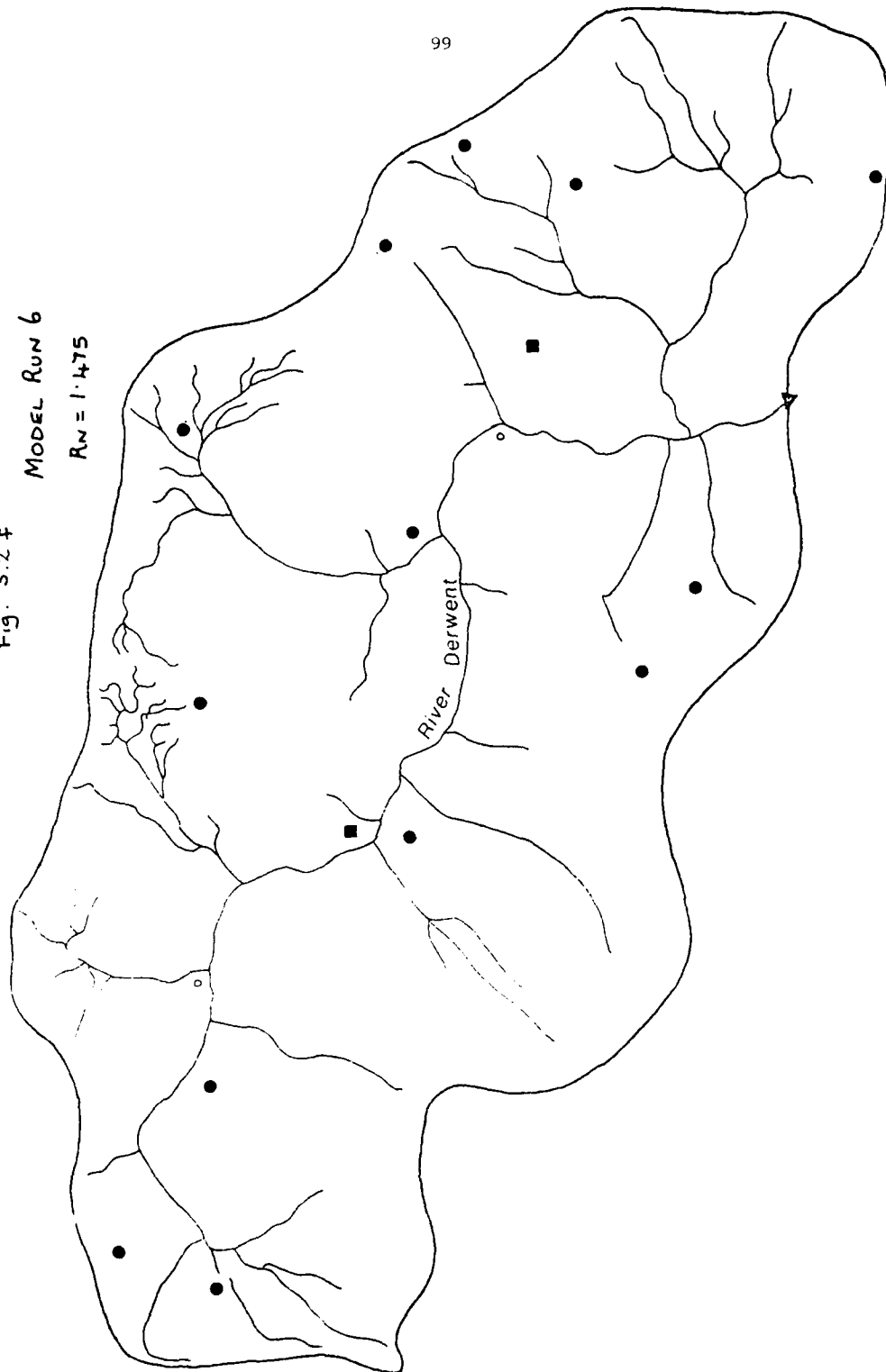


Table 3.5 (f)

MODEL RUN 6

A saturated model design would require 2042975 to be evaluated. This would require 68543 seconds of computer time.

Computed design in sequential order.

<u>Serial Number</u>	<u>Cell No.</u>	<u>Det. M.</u>	<u>Max. Var. Measure</u>
1	6		
2	21		
3	10		
4	20		
5	13		
6	14		
7	18		
8	2		
9	26		
10	27		
11	28		
12	12	0.95E-07	40.565
13	22	0.16E-06	35.000
14	29	0.24E-06	31.151
15	11	0.33E-06	30.530

Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12										
1	0.5205											
2	0.7128	-0.52										
3	0.3314	0.22	-0.36									
4	0.4043	0.44	-0.19	-0.21								
5	0.1728	-0.10	-0.32	0.09	-0.25							
6	0.1959	-0.23	0.40	-0.07	-0.07	-0.12						
7	0.2776	-0.14	0.40	-0.35	-0.07	-0.17	0.04					
8	1.0315	0.43	-0.63	0.39	0.13	0.22	-0.19	-0.71				
9	0.1667	0.28	-0.14	-0.12	-0.04	0.02	-0.12	0.15	0.08			
10	0.2845	0.18	0.04	-0.06	0.25	-0.41	-0.33	0.23	-0.17	-0.03		
11	0.5311	-0.12	0.37	-0.60	0.48	-0.14	0.14	0.09	0.14	-0.16	0.09	
12	1.5816	-0.65	-0.00	0.18	-0.67	0.29	-0.08	-0.11	0.08	-0.08	-0.10	-0.41
Term Number		1	2	3	4	5	6	7	8	9	10	11

Largest (Absolute) Correlation = -0.70 between Coefficients of Terms Nos. 1 and 12.

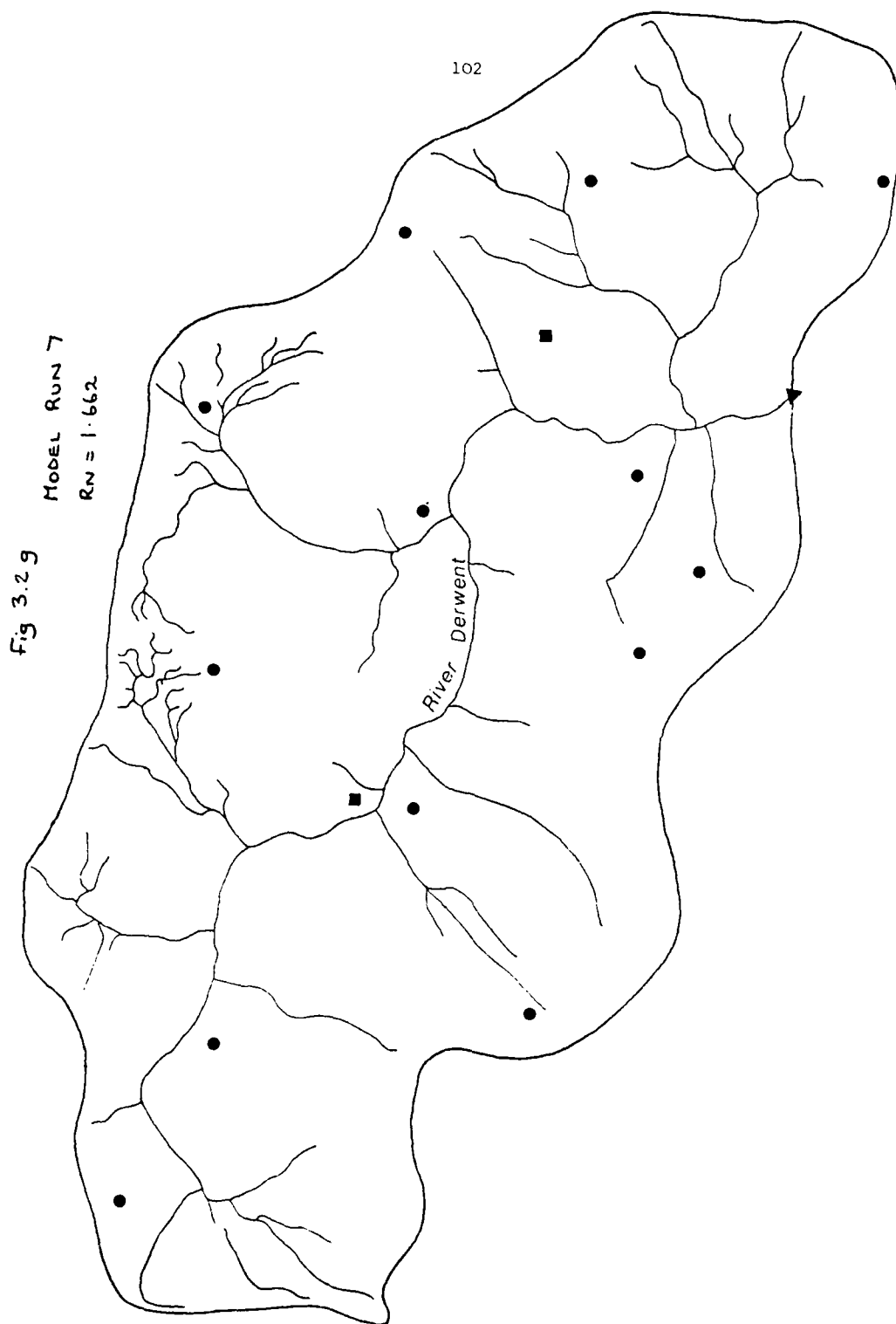


Table 3.5 (g)

MODEL RUN 7

No quadratics

Total number of terms in model: 11

Prespecified cells: 2

A saturated model design would require 3,124,550 combinations to be evaluated. This would require 85,222 seconds of computer time (£2,837.89).

2,200 random combinations calculated.

<u>Cell No.</u>	<u>Determinent</u>	<u>Max. Variance</u>
6		
10		
29		
13		
14		
18		
20		
27		
2		
11		
12	0.18E-05	72.034
22	0.53E-05	32.015
3	0.81E-05	32.093
26	0.000012	21.501
30	0.000015	19.801

Term No.	Inverse Diagonals	Correlation between Estimated Coefficients up to Term No. 12									
1	0.2208										
2	0.5897	-0.57									
3	0.2963	0.50	-0.52								
4	0.2494	0.09	-0.35	0.04							
5	0.1231	-0.08	-0.21	0.02	-0.08						
6	0.1978	-0.12	0.05	0.18	-0.09	0.13					
7	0.2093	-0.04	0.18	-0.06	-0.26	-0.10	-0.07				
8	1.6341	0.51	-0.56	0.32	0.42	0.14	0.17	-0.51			
9	0.1701	0.49	-0.33	0.23	-0.05	0.05	-0.03	0.04	0.39		
10	0.6845	0.16	0.03	-0.04	0.19	-0.44	-0.32	0.28	-0.21	-0.05	
11	0.4447	-0.58	0.42	-0.57	0.31	-0.02	0.06	-0.04	0.07	-0.24	0.03

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Largest absolute correlation -0.58.

To conclude, CAED provided a means of incorporating strict experimental design into the establishment of the rain gauge network. The selected gauge network (which appears on all rainfall maps presented for the Upper Derwent) thus provides a wide spatial coverage, whilst maximising the independence between those variables which describe each gauge site.

3.5.1 Summary of the hydrometric network used in this study

Casella autographic gauges were installed at all but two of the gauge sites in the Upper Derwent, together with standard Met. Office Mark II manual gauges (these were emptied weekly during each visit to service the gauges). As discussed previously, the autographic gauges have the advantage of relatively low cost, but the disadvantage of pen-and-ink charts which require digitising in order to provide the amount and timing of rainfall. In addition to the autographic and manual gauges at site A1, a manual rain gauge at ground level and surrounded by a Plynlimon pit and screen was constructed to provide a comparison between the pit gauge and the gravel surround used in this study. At two sites (A3, B5), tipping-bucket rain gauges with data loggers were installed: these provide an electrical output which is decoded to yield the real time of each tip. At A3 a Christie logger was used; output was decoded at the Polytechnic. At B5, a Data Research Services (DRS) logger was used: here cachettes are sent to DRS and a printout, specifically designed for tipping bucket rain gauges is produced. We regarded the DRS printout as the most reliable data we collected, a basis for interpreting the other data sources.

The outflow of the catchment (Slippery Stones) is monitored with a horizontal Ott stage recorder and a broad crested weir, owned by Severn Trent Water Authority. The stage-discharge relationship was established by the water authority.

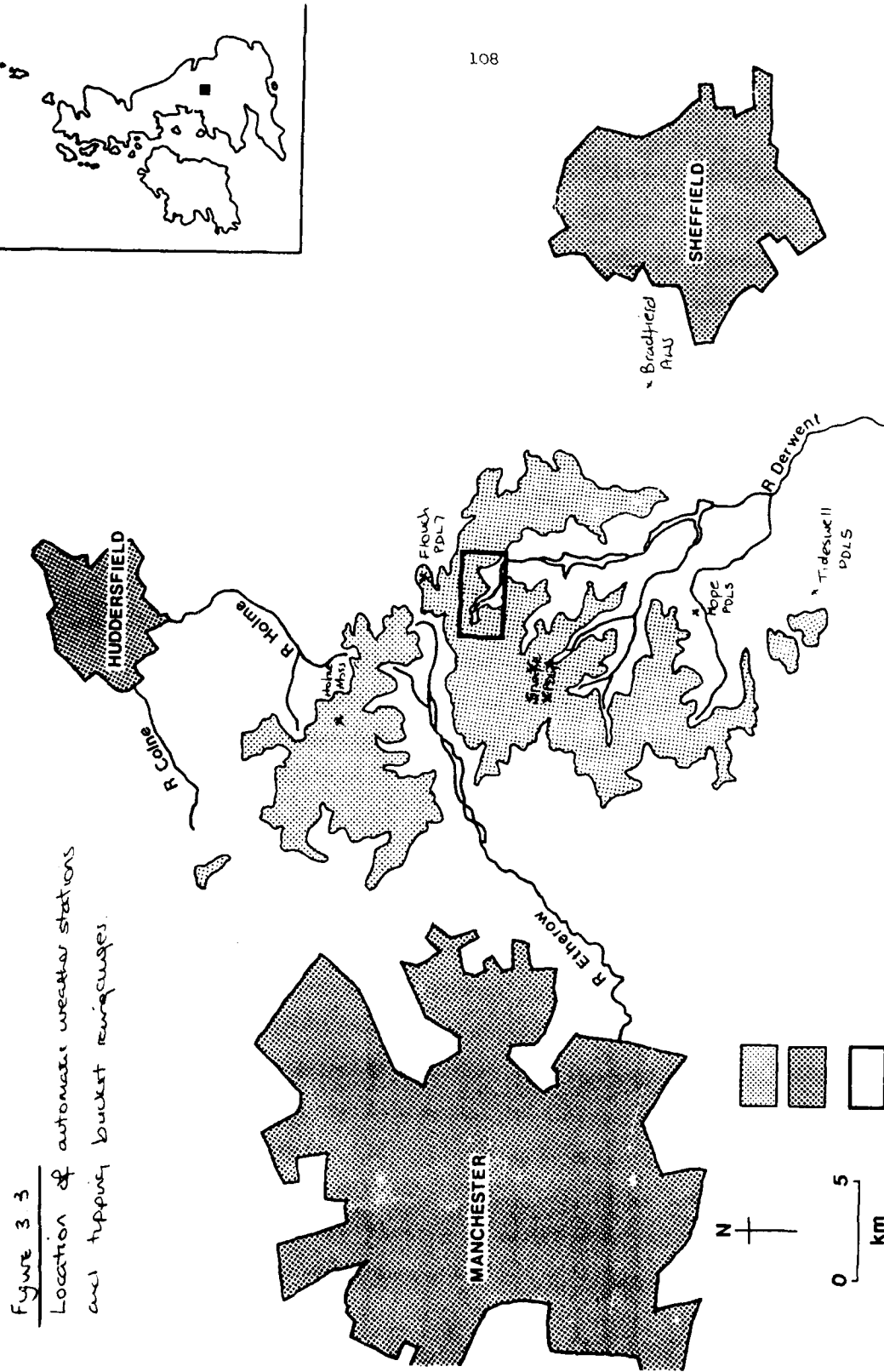
In addition to the Upper Derwent instrumentation, two solid state data loggers (PDL 7's) were installed to supplement the water authorities raingauge network on the South Pennines scale. The location of gauges and the availability of data from authority raingauge network is discussed in section 3.5. The two data loggers were installed to provide a real time comparison with the two data loggers within the Derwent catchment so that rainfall events could be traced as they moved across the area. The availability of suitable sites for these raingauges was severely restricted by the availability of accessible land and by the dangers of vandalism if cited in popular public areas. Ideally the raingauges could be in a line to the west and east of the Derwent catchment data logger. Unfortunately no site was available to the east so one has been installed to the north instead, at Ellerslie Bridge (grid ref 1982, 011). The PDL 7 data loggers are a modernised version of the P.D.L.5. installed in the Derwent catchment but which operate in the same way. The Ellerslie Bridge raingauge is installed at 30.5cm to Meteorological Office specifications. The site is well sheltered from all directions and so wind exposure is unlikely to affect gauge catch. Hence, there is no need to install the raingauge at ground level or within a turf wall. In contrast the second PDL7 is sited to the west of the Derwent catchment at Devils Dyke (grid ref 4098, 3937) at probably the most exposed location within the network. For this reason the raingauge offset is at 20.5cm above

ground level and surrounded by a turf wall. The turf wall is 12ft diameter and conforms to the Meteorological Office specifications for raingauges located at over exposed sites (Met. Off. 1969; Fig. 2.5). It was not practical for this raingauge to be installed in a dustbin at ground level as the Derwent catchment raingauges were because of its inaccessability and poor drainage. If installed in a dustbin at ground level the gauge would require weekly maintenance to pump out the collected water. Installed at 20.5 cm, the collected water is able to drain away and maintenance reduced to fortnightly or when the cachette needs replacing.

3.5.2 Raingauge network maintenance

The Casella autographic raingauges are fitted with daily gears so that 1.1 cm of chart is covered in one hour. When the clocks are fully wound they will last seven days. For this reason, the raingauges were visited at a minimum of once a week. On each visit the water collected in the dustbin is bailed out to ensure the raingauge will syphon. The contents of the Snowdon manual raingauge are also measured.

The method of raingauge installation described here has not been completely trouble free. At several sites, as the peat became increasingly saturated, the water pressure forced the dustbin up and out of the ground. Where this occurred the dustbins were replaced and held firm by two two-meter lengths of dexion forced into the peat at an angle and bolted to the dustbin. At a few particularly wet sites, when this was done the pressure started to crush the dustbin. Under these conditions if the gauge could not remain level and at the correct height, a new site was selected a few meters away on a more



freely draining area or where a pipe could be inserted to aid drainage.

A second problem is the high failure rates of the casella raingauges. Despite careful maintenance, the average weekly failure rate was 28% for 1982.

3.6 Other data sources

The need to measure the storm rainfall pattern on the larger Southern Pennines scale is met by the three Water Authority's (YWA, STWA, NWWA) raingauges. The densest network of raingauges available are the daily-read manual gauges (Met. Type II) with over 96 made available in a 2500 Km² area centred on the Upper Derwent catchment (Fig 3.4).

Daily rainfall data is however, a very coarse indicator of storm rainfall patterns as two or more storms may occur over the 0900-0900 rain day with widely varying synoptic conditions. They are useful nonetheless to relate to the Upper Derwent storage gauges and also to predict pattern on that temporal scale. Of more direct use, are the autographic raingauges and data loggers. Most of the water authority autographics are weekly gauges and of the tilting-syphon type. Although the time definition is less fine than those with daily gears, they can provide adequate information on an hourly basis. The data from three data loggers have also been made available for this project (D.R.S. PDL7's) which will again provide a very important time link across the area. Fig 3.3 shows the distribution of data loggers attached to tipping bucket raingauges.

The Meteorological Office (Malvern RRL) have made available the data from Hameldon Hill Radar. This is sited at 400 m OD, 47 Km north-west of the study area at Hameldon Hill. Rainfall at an intensity of

0.1 mm hr^{-1} can be measured over a radius of 7.5 Km. Hard copies of the rainfall estimate are made available using a 2 Km grid and at five minute intervals. Integrations are also available for the whole storm period for the calculation of total rainfall volumes. The estimates used are those which have been calibrated to the meteorological offices' best ability ie. using the five lowland check sites and the area factors (see Hill (1981)).

The Meteorological data were also provided by Malvern (Met RRL) for the Aughton station, particularly useful was the low level (700 mb) wind speed and directions. Sheffield University, Geography Department made available anemometer data from the Bradfield automatic weather station. This provided more local wind conditions. Other weather stations in the area include Glossop and Tideswell. S.T.W.A. planned to erect an A.W.S. at Little Moor (Site B5) from which anemometer data would also have been available; however, this offer never materialised. Measurements of cloud height and wind speed and direction were available from Holme Moss. This is the nearest site of measurements to the Upper Derwent catchment and will be used to estimate 'local' weather conditions. It was not possible to make continuous meteorological measurements within the Upper Derwent because of objections from the National Park Authority relating to the intrusion that instruments would make within the National Park area.

4. Analysis of Southern Pennine
Rainfall Patterns for 1981

4.1 Introduction

This section describes the analysis of a selection of "rainfall days" from 1981, and seeks to relate the influence of meteorology and topography on the rainfall pattern. For this period, only Water Authority data was available as the raingauge network described in Section 3 had not been installed. The major aims of this analysis is to relate rain type, wind speed and direction to the daily rainfall gradient and pattern over the Southern Pennines as a whole and to give a general idea of the type of variation that occurs.

4.2 Data Sources

4.2.1 Rainfall data

Forty-one daily raingauges were made available for this period of study by the local Water Authorities. Receiving the records directly from the Authorities, rather than via the Meteorological Office had mixed advantages. The data had not been quality controlled by the Meteorological Office which tends to remove extreme values by inter-station correlations and therefore possible storm centres of heavy rainfall are preserved. However, the data is thus subject to observer error. Comparisons between Meteorological Office and Water Authority figures for one site over the same period did not produce any major disparities.

All gauges were classified according to whether they are sited and maintained at Meteorological Office standards and whether protected by turf walls or Plynlimon screens when in over-exposed sites. Hill (1983) found that days in which the upwind rainfall rate was less than 0.5 mm/hr^{-1} the seeder rate was insufficient to create enhancement by this method.

In an attempt to eliminate these from the study, days when at least 10.0 mm fell at a minimum of one site were selected. Obviously, there is a chance that the 10.0 mm distributed evenly throughout the day (rainfall rate 0.24 mm/hr) could occur. However, this was checked for by reference to the period of rainfall from the radar data. A further problem is that the upwind rainfall rate may still be less than the 0.5 mm/hr, or threshold which Hill found to be important for the development of orographic enhancement.

Days with heavy snowfall were also omitted from the analysis on the basis that (1) the measurement of snowfall is extremely difficult with standard raingauges; there is also evidence to suggest some deviation from the Meteorological Office specification for measuring snow, (2) poor quality of rain gauge data during snowfall is matched with the as yet unsolved problems of adequately calibrating radar for bright band and snow conditions. For these reasons the whole of December 1981 was omitted from the analysis and several days of widespread snowfall during the winter months. The remaining ninety-six days of the year were checked for errors and missing observations. Eighty-four days were error free and suitable for the following analysis.

4.2.2 Characteristics of rainfall

Hameldon Hill radar data was used for determining

- a) the period during which rain fell;
- b) type of rain
- c) direction of movement.

The availability of information on when rain was occurring in the area enabled rainfall events crossing into two raindays (0900-0900) to be omitted, or grouped together if other conditions remained constant. The radar was also used to classify raindays according to whether rainfall was a) widespread or b) showers and bands. On some occasions, the type of distribution changed during its progress. Under these circumstances, the day was classified by raintype persisting for the longer period of time. This assumes that both raintypes are of equal importance in determining the rainfall distribution. As no evidence was available to the contrary this method was utilised. Direction of storm movement could be determined from consecutive radar scans.

4.2.3 Synoptic type and wind characteristics

Synoptic type was taken from the Daily Weather Summary, as was low level wind direction. Wind direction was initially classified into three directions, on the basis of the work by Hill (1981):

- a) $135^{\circ} - 202^{\circ}$
- b) $225^{\circ} - 315^{\circ}$
- c) $315^{\circ} - 135^{\circ}, 202^{\circ} - 225^{\circ}$

These were later found to be too broad and were later refined (see later comments).

Low level wind speed was initially classified according to (1) light to moderate and (2) strong; again, this classification was subdivided later. When wind speed changed during the day, preference was given to the wind speed which occurred during the period when rain was falling or, if this information was not available, to the most persistent wind direction.

The choice of days and classification of parameters under consideration, produced an uneven distribution of types. For example 94% of the days under investigation were classified as having wind speeds in the category 'light to moderate'. Similarly, only 14% of days (12 occurrences) were classified as having a SW-NW wind. Table 4.1 gives a complete breakdown of the classifications.

Table 4.1

Classification and Frequency of Occurrence of Meteorological Conditions for Days with 10.0 mm Rainfall at a Minimum of One Site.

Rain type	Total Days	% Days
1 Showers, bands	55	65.47
2 Widespread	29	34.52
<u>Wind speed</u>		
1 Light, moderate	79	94.04
2 Strong	5	5.95
<u>Wind direction</u>		
1 135-202	12	14.28
2 225-315	43	51.19
3 315-135, 202-225	29	34.52

Each day was classified according to wind speed, direction and raintype (Table 4.2). Four combinations did not occur during the period under investigation (ie. did not produce more than 10.0 mm rain at one site); there were showers with strong winds in 135-202°, or with a wind direction between 315-135° and 202-225°. This makes statistical conclusions about the data difficult to make hence the case study approach to the analysis.

Table 4.2

Combinations of Meteorological Conditions and Their Frequency
of Occurrence for the 1981 rainfall days selected

Rain Type (1)	Wind Speed	Wind Direction (2)	% Days	Total Number
Showers	Light-Moderate	225-315°	30.95	26
Widespread	Strong	225-315°	1.19	1
Showers	Strong	225-315°	4.76	4
Widespread	Light-Moderate	225-315°	14.28	12
Showers	Strong	135-202°	0	0
Widespread	Light-Moderate	135-202°	3.57	3
Showers	Light-Moderate	135-202°	10.71	9
Widespread	Strong	135-202°	0	0
Showers	Light-Moderate	315-135°	19.04	16
Widespread	Light-Moderate	315-135°	15.47	13
Showers	Strong	315-135°	0	0
Widespread	Strong	315-135°	0	0
			100	84

(1) Showers includes 'showers and bands'

(2) 315-135° includes 202-225°

4.3.1 Calculation of Rainfall Gradients

Scattergrams were produced between raingauge altitude (M.O.D.) and daily rainfall totals (mm) for each of the days under investigation, to check the distributions for their suitability for linear correlations. As noted by Burt (1980) working on Pennine rainfall, curvilinearity was present but was not felt to be pronounced enough to violate the assumptions of linearity.

Pearson correlation coefficients were calculated for each of the ninety-six days for all the sites (41). The slopes of the regression line (b) from the regression equation

$$y = a + bx$$

was taken as the rainfall gradient (mm/100 m).

Rainfall gradients ranged from a maximum of 8.3 mm/100 m (February 2nd) to a negative gradient of 0.3 mm/100 m (May 27th). The correlation between mean daily rainfall and daily rainfall gradient for eighty-four cases is 0.47, illustrating a tendency for the rainfall gradient to increase with increasingly large storm totals. Isoline maps of daily rainfall show that of the two major areas of high ground in the study area Kinder Scout (636 m) and Black Hill (533 m) seldom have similar rainfall totals. On many occasions the rainfall gradients in the two areas are different and this reduces the correlation coefficient. The correlation between mean rainfall and the range in rainfall over the area is 0.74. This perhaps suggests that the higher-total storms are associated with major enhancement in upland areas.

4.3.2 Rainfall Patterns

The eighty-four rainfall gradients produced a generalised picture of the enhancement in rainfall with increasing altitude. It does not, however, say anything about the spatial pattern of rainfall over the area. The correlation coefficient (r) and the standard error (E) give an indication of the goodness of fit but the distributions require some expression of pattern. It is impractical to describe the rainfall distribution for each day so, a grouping method was required to reduce the number of maps to be drawn up. The method chosen was factor analysis. This technique

enabled the identification of any underlying pattern in the data set, using Q mode factor analysis (Burt, 1980). This provided a method to objectively group days which had similar rainfall patterns. The method and assumptions of this technique are discussed in appropriate statistical texts (eg. CATMOG 7).

A matrix was produced for input to the package with rainfall site locations (41) as cases, and rainfall days (96) as variables. Factor one accounted for 37.6% of the variance and factor 2, 12.8%. These correlated at 0.81 and 0.3 respectively with altitude. The first five factors together accounted for 70.2% of the variation (factor 3 = 10.6%, factor 4 = 4.8% and factor 5 = 4.4%). Factor 1 was clearly identified as representing days with an orographic component; labelling the other factors proved to be difficult.

A cross-tabulation did not initially indicate any underlying process in the groupings produced by the factor analysis with respect to wind speed, direction or rain type. A closer inspection of the method by which the meteorological parameters had been classified, particularly wind direction, led to some light being shed on the naming of the factor groupings. Predominant wind direction was classified according to eight directions (Table 4.3), plus a ninth category with winds classified as variable. Taking those raindays with a correlation with the factor of above 0.6 (ie. those days most similar to that factor), the factors could be labelled. Fifty-four percent of the members in factor 1 were characterised by southerly wind directions with 12.5% and 4.2% respectively with south-west or south-easterly winds. In contrast, 40% of the members of factor 2 had westerly winds and only 12% with southerly winds. Factor 3 has only ten members which correlated at 0.6 with that

factor. Of these, three had south west wind directions and two a south-easterly direction. Table 4.4 shows a complete breakdown of factor members by wind direction.

Table 4.3

Breakdown of Factor Members by Wind Direction

* Factor members where $r \geq 0.6$

Dominant wind direction	1 (%)	Factor 2 (%)	3 (%)
S	13 (54.2)	3 (12)	1 (10)
SW	3 (12.5)	4 (16)	3 (30)
SE	1 (4.2)	0 (0)	2 (20)
N	0 (0)	0 (0)	1 (10)
NW	2 (8.3)	3 (12)	0
NE	0 (0)	0 (0)	0
E	2 (8.3)	1 (4)	0
W	2 (8.3)	10 (40)	0
Variable	1 (4.2)	2 (8)	3 (30)
	24(100)	25(100)	10(100)

Having identified groups of days with similar rainfall distributions and related the groups to wind direction, it was necessary to see what spatial expression this had. A number of storm total rainfall maps, characteristic of each factor grouping were produced using a SYMAP package. This offered the advantage of both speed and objective contouring. Two major patterns could be identified corresponding with

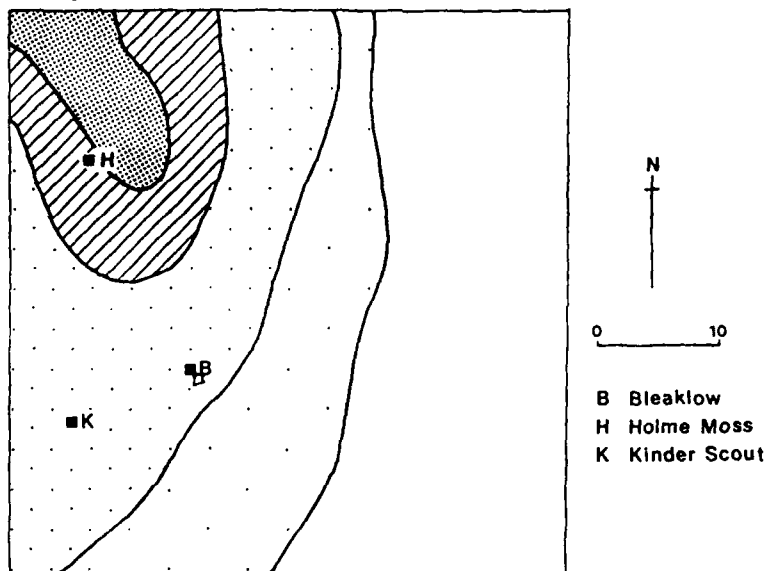
factors 1 and 2. Factor 1 raindays are characterised by higher rainfall totals occurring in the north west of the study area with very low totals on the lowland to the west of the major (Pennine) divide. Factor 2 is characterised by greater totals in the southerly part of the study area. These can be represented by a generalised map (Fig 4.1).

Type one rainfall distributions, characterised by predominantly southerly or south westerly winds show very little enhancement over the two southern uplands, Kinder Scout and Bleaklow. Air masses from this direction will tend to be least sensitive to enhancement having travelled long distances over land. Under these circumstances, enhancement may have already occurred over Wales before reaching the Southern Pennines making the air mass increasingly less sensitive to high ground. On some days slightly higher totals do occur in the southern part of the study area but still comparatively low compared to the Holme Moss area. The Holme Moss - Black Hill area, although lower than Kinder Scout may be receiving the increased totals as a result of carry over from Kinder Scout. Strong wind speeds may carry the cloud beyond Kinder Scout and on to Holme Moss by the time it is precipitating. This may be further supplemented by the added lift caused by the presence of Holme Moss. Thus, Holme Moss in southerly winds, may be receiving enhanced rainfall as a function of its location in respect to Bleaklow and Kinder Scout rather than or in respect to its own altitude.

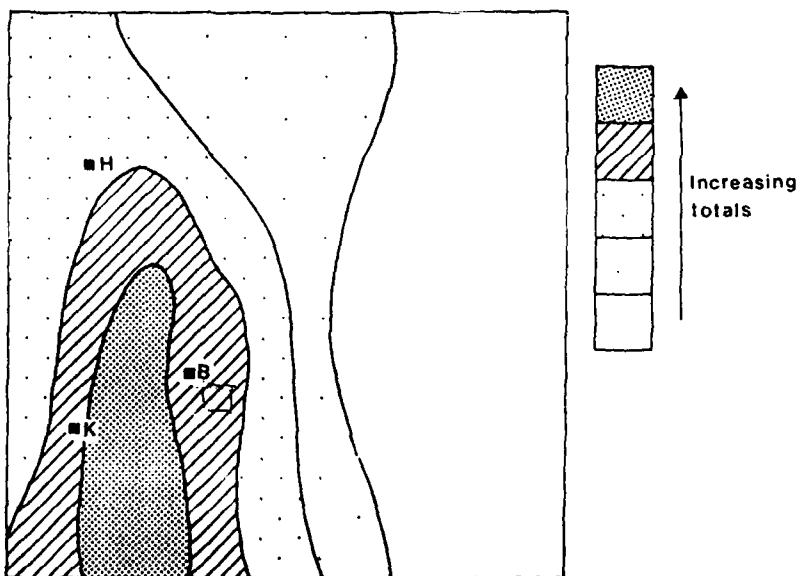
Type two rainfall distributions, typified by higher rainfall totals in the southerly part of the area tend to have westerly winds. The lack of enhancement over Blackhill/Holme Moss area is surprising when considering their location in relation to the air mass passage. A

Fig 4.1 GENERALISED RAINFALL PATTERNS

A. Type one distribution



B. Type two distribution

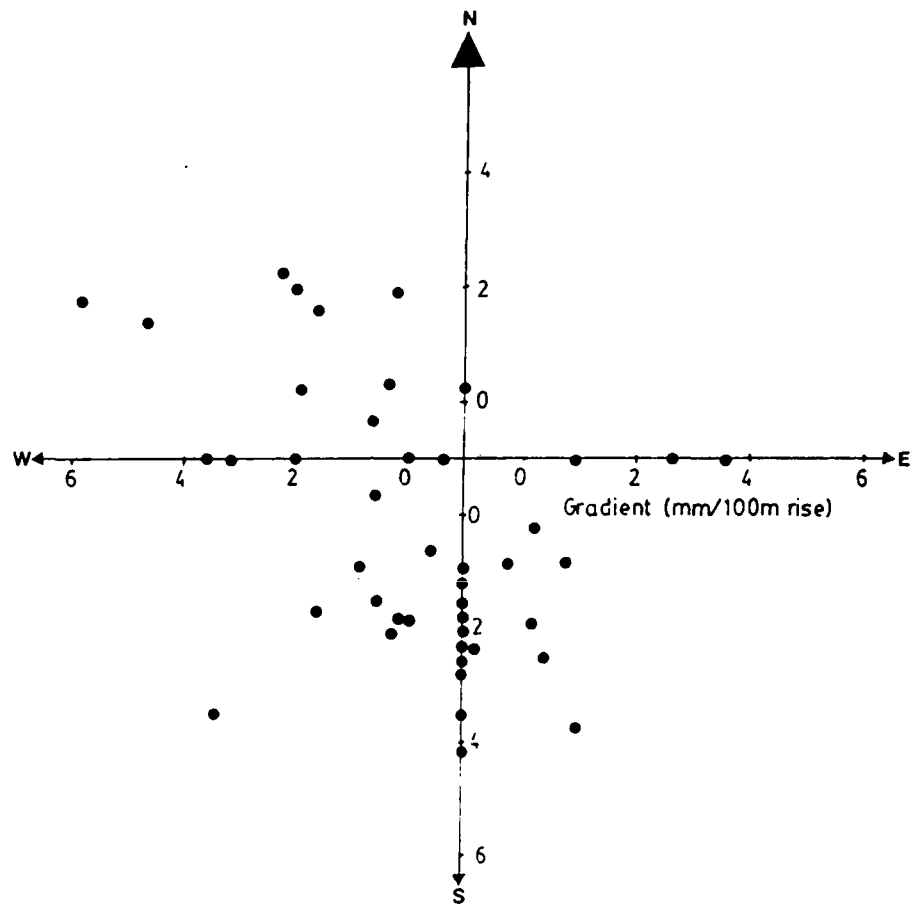


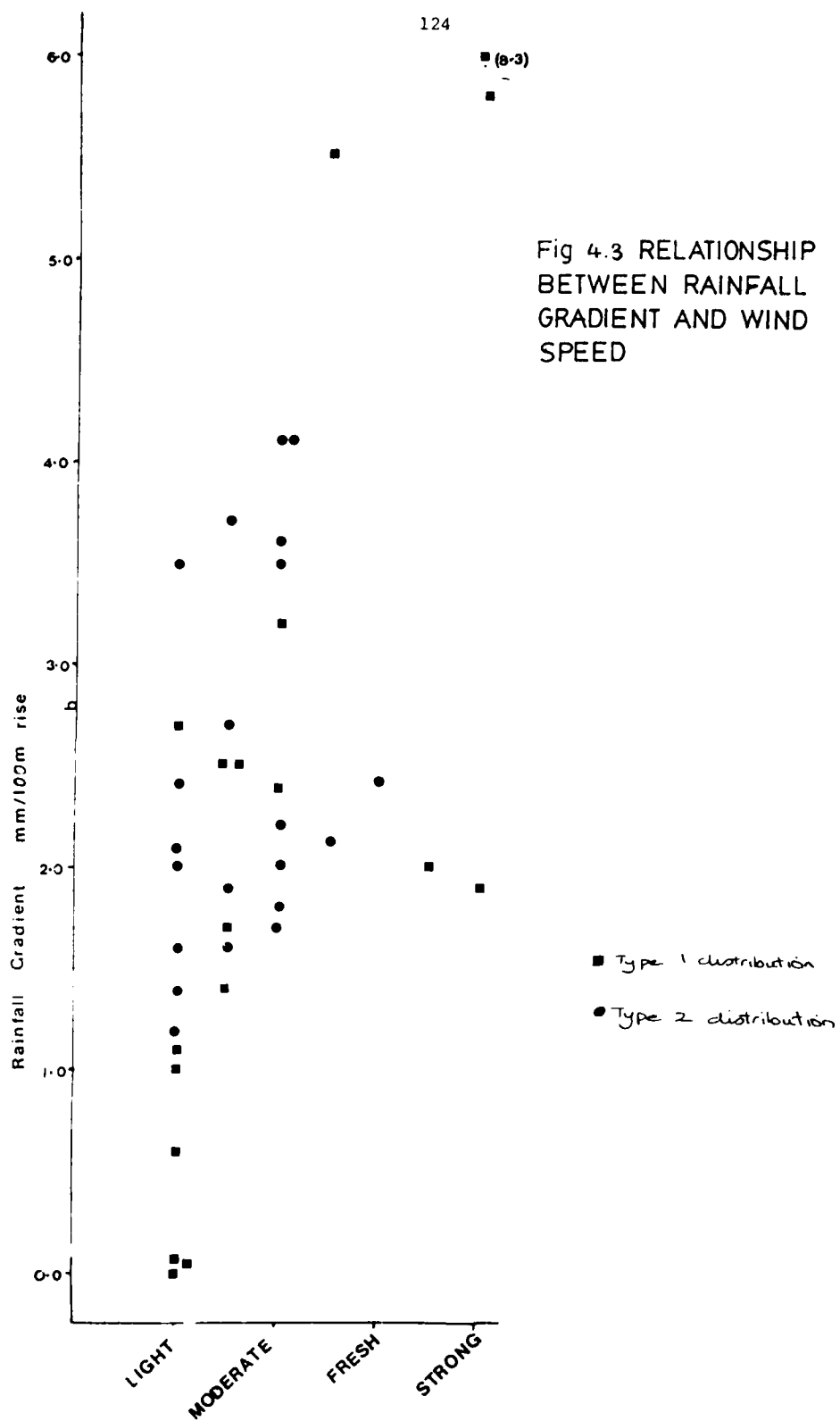
westerly or north westerly wind would encounter no major barriers until the Southern Pennines. It would then tend to be vulnerable to even fairly low barriers. It is possible that the lack of enhancement over Holme Moss is a result of the "carry over" effect, although Holme Moss is a smaller, and lower, upland area than either Bleaklow or Kinder Scout. Overall, the significance of the factor analysis results is not totally clear, except that the dominant factors are positively correlated with altitude. Since the factor analysis is necessarily biased with respect to the location of available gauges (for in uplands, especially on Kinder Scout) and to the storm events observed, the analysis may not indicate the most significant pattern in hydrological terms, simply the most common pattern. Nevertheless, taking the dominant factors together with other information, such as rainfall gradients, suggests a dominant orographic component at the storm timescale.

4.4 a) Relationship between rainfall gradient and wind direction

Sixty-four percent of the days analysed with rainfall gradients greater than 3.0 mm/100 m had wind directions within the category 225°-315°. Of the days with rainfall gradients exceeding 4.0 mm/100 m (8 days), all had wind directions within this category (Figure 4.2). The lack of winds from 360°-90° makes it impossible to infer about their ability to enhance rainfall over the high ground. However, it is significant that the highest rainfall gradients have occurred from a west-north-west direction as this is the shortest land route before the high ground of the Pennines. The air from this direction is likely to be very moist and hence susceptible to orographic enhancement. It is likely that strong winds from the north east would produce high rainfall gradients, on the same principle. Unfortunately this could not be tested as no days with

Fig 4 2 RELATIONSHIP BETWEEN RAINFALL
GRADIENT AND WIND DIRECTION





more than 10.0 mm rain occurred at one site with north easterly winds during 1981.

b) Rainfall gradient and wind speed

All days with higher rainfall gradients had wind speeds exceeding 'moderate to fresh'. This would tend to confirm that found by other authors that enhancement requires strong low level winds. This is further confirmed (in a negative way) by the fact that no days occur in which there is a low wind speed (less than 'light to moderate') and a high rainfall gradient (Fig 4.3).

c) Relationship between wind speed and direction and rainfall gradient

All days with high rainfall gradients, exceeding 4.0 mm per 100 m rise are associated with frontal systems and characterised by winds exceeding 'fresh' (Table 4.4).

Table 4.4

Relationship between rainfall gradient and meteorological conditions

Date	Gradient mm/100m	Wind Direction	Wind Speed	Rain Type	Synoptic conditions
Jan 1	5.8	W - NW	Strong	Showers/bands	WF
Jan 2	6.5	W - NW	Strong	Showers/bands	CF
Jan 16	4.3			Widespread	
Feb 2	8.3	SW - WNW	Fresh-light/mod	Showers/bands	CF
Mar 23	4.1	SSE	Moderate	Showers/bands	Frontal
Oct 8	4.1	S'erly	Moderate	Showers/bands	CF
Oct 9	5.5	SW	Fresh-moderate		
Nov 26	4.2				

4.5 Conclusions

The time scale of analysis, namely the rainfall, limits the amount of detail that can be extracted. Also, the limited size of the sample produced some problems. For example, no days occurred in which strong easterly winds were recorded. This makes statistically valid conclusions impossible to make but some trends can be identified.

- a) The dominant pattern identified by factor analysis was that of storm rainfall distributions closely relate to altitude, at the Sputhern Pennine Scale.
- b) Highest rainfall gradients tend to occur when the wind speed exceeds 'moderate to fresh'. No days with low wind speeds (less than 'light to moderate') have high rainfall gradients.
- c) Higher rainfall gradients tend to occur when the wind is in the sector 225° - 315° than from any other sector. However, this may in part be a result of inadequate samples from other sectors.
- d) Two major types of rainfall pattern can be identified:
 - i) high rainfall in the north west of the area with very low totals over the lower ground to the east; 67% of these days have southerly or south-westerly winds.
 - ii) high totals to the south (Kinder area) with a tendency for winds to be westerlies.
- e) Mean daily rainfall is correlated significantly with the rainfall gradient, suggesting that wetter days have additional rainfall enhancement in upland areas.

The study of 1981 rain days has provided some insight into the patterns of rainfall distribution over the Southern Pennines and their associated meteorological parameters. It has confirmed to some extent that found

by other authors that orographic enhancement is controlled by the supply of moist air, usually provided by strong low level winds. The main deficiency of the study relates to its coarse temporal scale, and to the sparse network of gauges used, especially for higher ground.

Chapter 5 Results

5.1 Introduction

This chapter describes the results of analysis of data collected from the raingauge networks. The chapter has been divided where possible into the two scales: Firstly, the Upper Derwent scale using the raingauges installed specifically for the project; and secondly, the southern Pennine scale. Although the same storm is often analysed at both scales, this division was used to avoid confusion between the results.

5.2 Description of the data

5.2.1 Sample size and characteristics

An unusually dry summer in 1983 restricted the number of viable rainfall events to approximately 30 making a full statistical analysis difficult. However, those available are from a number of synoptic types and therefore provide a good range of events for comparison. Unfortunately no "pure" orographic event was monitored with the Upper Derwent network (a "pure" event involves feeder-seeder mechanisms only; no potential instability is triggered). On the only occasion that such an event occurred, late December 1983, the autographic network was closed down for protection against frost. Some characteristics of this event could, however, be studied from data loggers installed for the project and by utilising Water Authority autographics which were operational at the time.

5.2.2 Upper Derwent storm totals

The 30 rainfall events recorded by the Upper Derwent network were checked for those in which there was an obvious presence of snowfall. As standard autographic and manual storage gauges are notoriously inadequate

for measuring snowfall, particularly at exposed sites, such events were not investigated further. In cases where the autographic chart failed for some reason, and no further rainfall events occurred before gauge maintenance, then the manual gauge total has been used instead of the autographic chart total, thus enabling maximum information to be extracted from the network.

Table 5.1 provides a summary of the characteristics of the storms measured over the Upper Derwent, for which further analysis was undertaken. The arithmetic mean rainfall ranges from only 3.4 mm (17.7.83) to 43.7 mm (2.9.83), with a wide variation in rainfall duration. The sixth column of Table 5.1 gives an idea of the degree of variation in rainfall intensity found during the storm. This is based on the peak hourly rainfall intensity and is the difference (in mm hr⁻¹) between the gauge with the highest intensity and that with the lowest at the same hour. The largest difference is that of 11.8 mm occurring during the storm of 9.9.83.

To illustrate the variation in rainfall pattern without being influenced by individual gauge rainfall totals, all storm totals were converted to a percentage of the basin mean rainfall for those events. For this purpose, basin mean rainfall has been taken as the arithmetic mean of all the Upper Derwent autographic raingauges operating at that time. When the basin mean and +20% and -20% of the mean are plotted on maps in isohyetal form the general trend in rainfall distribution is clearly visible.

The major variations in storm total distribution with the Upper Derwent catchment tends to be in an east-west direction. Three distinct patterns are apparent;

Table 5.1 Rainfall Characteristics for storms observed in the Upper Derwent

Storm Date	Mean basin rainfall (mm)	Storm duration (hours)	Mean rainfall intensity (mm/hr)	Peak intensity, site	Max difference over basin at peak intensity*
12.5.83	6.4	6	1.07	3.04(C7)	1.3
28.6.83	7.8	15	0.52	1.8 (E15)	1.4
1.7.83	10.6	11	0.96	3.8 (C8)	3.3
17.7.83	3.4	11	0.31	4.1 (E14)	4.1
31.7.83	7.1	15	0.47	2.5 (D10)	2.0
16.8.83	19.9	17	1.2	6.5 (C8)	4.6
2.9.83	43.7	36	1.2	9.0 (B6)	8.1
8.9.83	10.6		0.62		
9.9.83	33.2	24	1.38	16.9 (E12)	11.8
7.10.83	8.8	9	0.98	3.9 (E15)	3.4
8.10.83	25.7	23	1.1	5.8 (B6)	5.3
15.10.83	17.0	10	1.7	6.5 (C8)	4.8
16.10.83	14.9	15	1.0	5.5 (C9)	5.5

*see text for explanation

- i) high rainfall (greater than twenty percent of the basin mean) in the west of the catchment declining in an easterly direction to only 80% of the basin mean
- ii) low rainfall in the west increasing in an easterly direction
- iii) high rainfall in the centre of the catchment declining both to the west and east

A fourth category can be identified, comprising those events with no large variation in rainfall receipt over the catchment. Two events do not fit into this classification, one displaying a strong cellular pattern (17.9.85) and the other (1.7.85)

It is thus evident from this classification that most storms show quite a large degree of spatial variation in rainfall over the catchment and that of the storms sampled, those displaying at least a 20% variation about the mean were in the majority.

5.2.3 Relationship between storm total distribution and synoptic meteorology

Table 5.2 lists the four categories of storm rainfall distribution, the degree of rainfall variation as a percentage of the basic mean and finally, the broad synoptic situation apparent with the crude level of information available. Links may be found if, for the Southern Pennine scale, regional wind speed and direction were available. On the Derwent scale, local wind speed and direction may help give a broad idea of the part of the catchment likely to receive enhanced totals but not, the detailed pattern as seen later.

Table 5.2 Storm rainfall categories and associated synoptic conditions

	Date	+ 20% variation	Synoptic condition
i)	High rainfall in west		
	28.6.83		weak trough
	17.7.83		thunderly low pressure
	31.7.83	110%, 80%	thunderly cold front
	16.8.83		warm front
	31.8.83		low pressure cold front
	2.9.83		low pressure
	16.9.83		low pressure
	7.10.83		cold front
	8.10.83		active fronts
	15.10.83		
ii)	High rainfall in east		
	17.5.83		
	9.9.83		low pressure
	16.10.83		
iii)	High rainfall in centre		
	27.5.83		occluded front
	14.6.83		
iv)	Unclassified		
	1.7.83		weak warm front
	8.9.83	no variation	
	17.9.83	cellular	warm front, cold front
	20.9.83	no variation	
	2.11.83	no variation	weak warm front

5.2.4 Relationship between storm total distribution and topography

As noted previously, many authors have identified the influence of topography on rainfall receipt, although the majority of these studies involve longer time periods, larger areas and less dense raingauge networks than that involved here. If a simple relationship between rainfall and topography, whether causal or incidental, can be identified it would greatly assist in the calculation of basin or sub catchment mean rainfall. To this end, each raingauge site within the Upper Derwent has been characterised by the following topographic and locational variables:

Location	{	northing	- northing grid reference
		easting	- easting grid reference
site	{	spot height	- gauge altitude (m)
character		slope angle	
		sine slope aspect	
		cosine slope aspect	
local	{	distance to divide	- distance (m) to nearest basin watershed (DISTDIV)
character		distance to west divide	(DISTWEST)
		maximum altitude	within 2 km radius
		direction of highest ground	within 2 km radius
		distance to Bleaklow	- km straight line (BLEAKLOW)
		height of highest ground	within 1 km radius (H1KM)

These were selected for their possible influence on raingauge catch. However, many of these variables were cross correlated rendering the total group of limited value for regression analysis. Table 5.3 identifies all those combinations with a correlation coefficient exceeding 0.55. Simple linear correlation were first carried out between each storm and all the topographic variables listed above. The results of this are tabulated in Table 5.3. It is apparent from the correlation matrix (Table 5.4) that those variables that characterise the individual raingauge sites have, in nearly all cases, no influence whatever on the

Table 5.3 Pearsons Correlations exceeding 0.55 between topographic and locational variables used in the Upper Derwent raingauge network

	Easting	Bleaklow	Alt2km	Distwest	Distdiv	H1KM	spotheight
Easting	-						
Bleaklow	0.99	-					
Alt2km	0.68	0.68	-				
Distwest	0.62	0.61		-			
Distdiv					-		
H1KM			0.71			-	
Spotheight					0.73		-

[variable names as defined in text]

catch of the raingauge. This is to be expected if all gauges are installed so that they are not unduly sheltered or infringe other installation criteria laid down by the meteorological office recommendations. As these variables only involve the immediate raingauge site, the scale of the topographic features are too small and localised to influence the rainmaking processes. Those variables characterising a wider area around the raingauges show stronger associations with storm totals but, in no consistent way.

Taking those variables that represent the wider topographical areas, generally stronger correlations were found. Correlations between 'distance to divide' and storm totals were mostly below 0.55 and only on one occasion (July 31) was the 95 percent confidence level reached ($r=0.655$). 'Distance west to divide' however shows a different pattern. On six occasions the significance level exceeds the 95 percent confidence

level. This is because there is a greater directional bias to this variable which, to some extent, reflects the normal rainfall distribution. 'Distance to Bleaklow' shows a similar pattern to 'distance west to divide' (these two independent variables are correlated at $r=0.61$). Similarly, 'Easting' and 'Distance to Bleaklow' are correlated at $r=0.62$ and thus show a similar trend when 'Easting' is correlated with storm total. The correlations between those variables depicting the east-west trend confirm the rainfall pattern described earlier (section 5.2.1) using percentage of basin mean.

Taking the altitudinal variables, only those which represent the general form of the hills have any apparent association with gauge catch. Spot height, for the reasons of its more localised bias, has no strong correlations with storm total. Correlations with 'maximum height within 1 km' and 'maximum height within 2 km' radius show quite strong associations, some of which are significant. In most of these cases, the 2 km radius variable had a stronger association than the 1 km radius variable. This seems to confirm that the storm rainfall distribution is not determined at a "local" scale. It is irrelevant here to try correlations with maximum altitude within 5 km radius since, because of the size and shape of the catchment, in most cases this will be the same for each gauge. ie. the high ground of Bleaklow. Already at the 2 km radius scale Bleaklow frequently dominates.

An attempt was made to calculate rainfall gradients using the slope of the regression line between raingauge catch and spot height. However, on many occasions, the correlation was too poor to yield meaningful results.

5.3.1 Hourly rainfall: Upper Derwent

The repeatable rainfall patterns observed over the Upper Derwent when total storm rainfall is measured suggest that the pattern might be maintained at smaller time scales. All events showing a variation in rainfall total over the catchment have been analysed at hourly intervals and some to 15 minute periods to identify how the total rainfall pattern is formed.

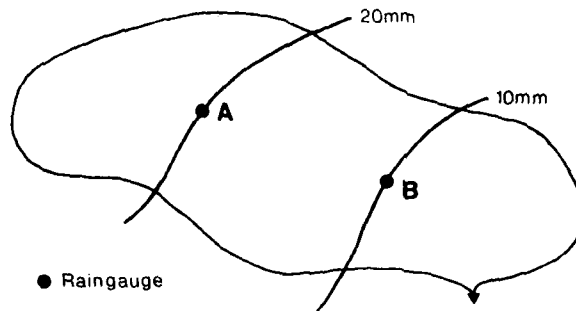
Daily autographic charts were used in the field to enable fifteen minute rainfall intensities to be extracted. However, the chart had to be left on the raingauges for seven days, which on many occasions made deciphering the lines very difficult. In addition, a complete revolution of the clock drum was not a convenient time division, so that extraction of the correct time of the start of rainfall especially after several days was often difficult. However, in cases of doubt the data logging raingauges provided a reliable check on the initiation, cessation and general characteristics of rainfall in the area. Despite this it was felt that fifteen minute rainfall totals were really at the limit of accuracy of the Casella charts both because of operator error in placing the pen on the chart and in clock accuracy. For this reason most analysis has concentrated on hourly rainfall totals.

5.3.2 Hourly rainfall intensities

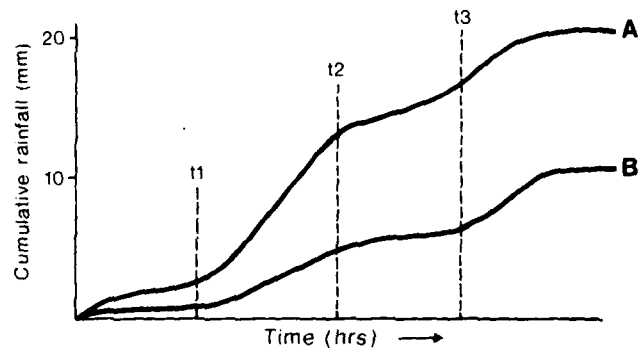
The storm total rainfall pattern observed over the catchment in many cases, was not an aggregate of sustained, consistent differences in rainfall intensity for the duration of the event. The more common occurrence was for the hourly rainfall intensities to be broadly similar over the catchment but with sudden intense bursts of rainfall boosting

**Figure 5.2 COMPOSITION OF STORM TOTAL RAINFALL PATTERNS:
A SCHEMATIC REPRESENTATION**

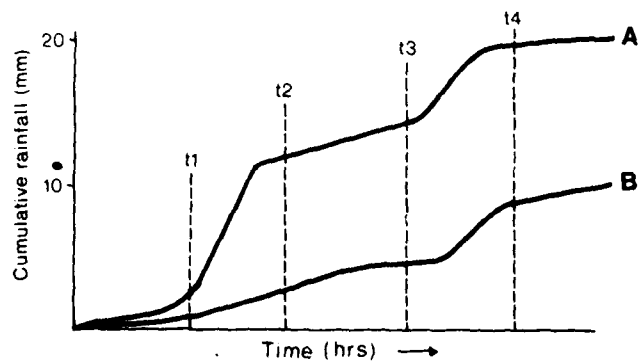
(1) Storm Total Rainfall



(2) Consistently different intensities



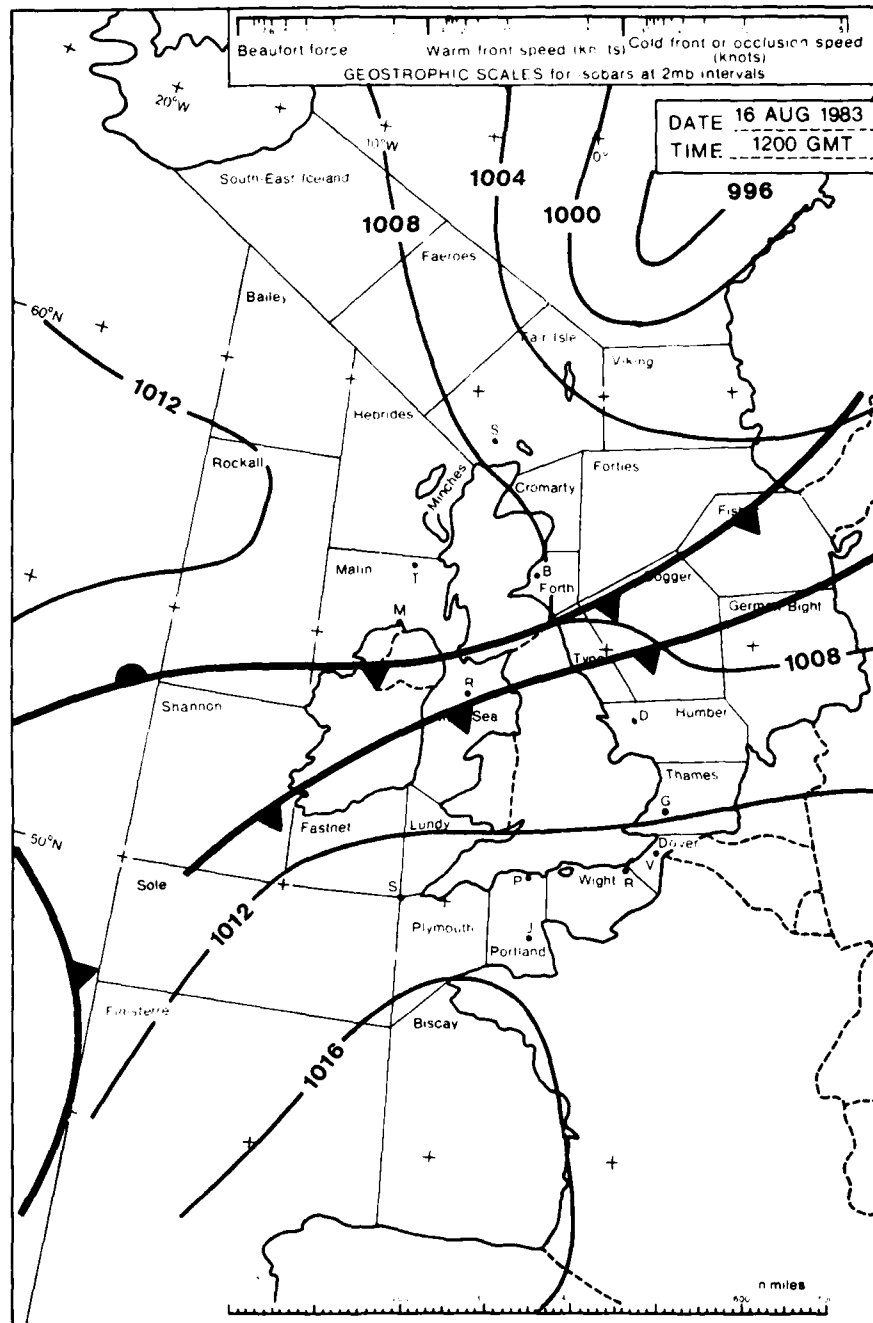
(3) Similar intensities with irregular high intensity burst at site A



the storm totals in some areas. This is illustrated schematically in Figure 5.2 . Taking two raingauges at opposite ends of the catchment in which one gauge (gauge A) is within the higher rainfall area and the other (gauge B) in an area of lower rainfall receipt, two examples of how this storm total rainfall pattern could be constructed, are illustrated. In the first case (Fig. 5.2.2) the lines of cumulative rainfall follow a similar pattern. However, the rainfall intensities are different throughout the duration of the storm by a consistent amount eg. by x mm/hour. Thus, after n hours the rainfall totals at the two raingauges are different. In the second case (Fig. 5.2.3), the hyetographs are markedly different. From time t_1 to t_2 , gauge A receives a sudden burst of high intensity rainfall which boosts the cumulative rainfall total well above that at gauge B. Between t_2 and t_3 the rainfall intensities are broadly similar and therefore adds the same amount of rainfall to both gauges. However, between t_3 and t_4 a burst hit both gauges but is more intense and of a longer duration at gauge A thus adding further to the already higher cumulative rainfall totals. From these two examples it is clear that a given difference in storm total rainfall over the catchment can be achieved from markedly different processes. From the cases recorded in the field, the latter of the two processes appears to be the more common ie. sudden intense bursts adding a relatively large amount to the storm total.

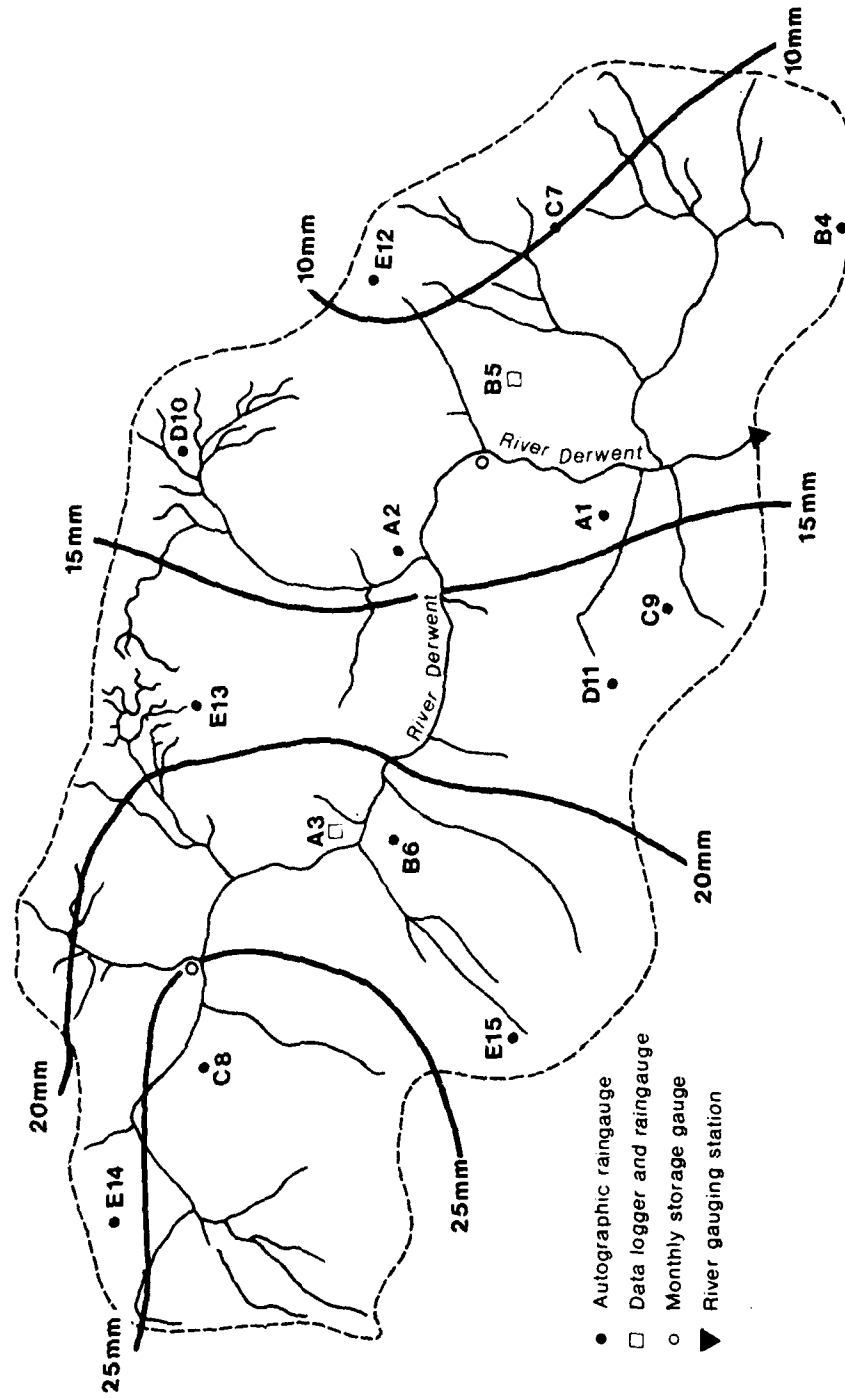
The schematic diagrams are naturally over-simplified to illustrate the range of variation possible. In the field, a degree of both processes is present but, the outstanding contributor to the spatial variation in storm total rainfall receipt are the sudden bursts of high intensity rainfall over only parts of the catchment.

Figure 5.3 SYNOPTIC CHART FOR 16.8.83



Redrawn from Meteorological Office Material.

Figure 5.4 STORM TOTAL RAINFALL 16.8.83



The following case studies have been taken as representative of the type of events recorded. They illustrate the spatial extent and intensity of rain cells and the resultant within storm rainfall variation over the catchment.

Case Study: August 16 1983

On the rain day 16.8.83 trailing warm and cold fronts, with an associated rain band, moving gradually in a south-easterly direction, produced high rainfall totals over the southern Pennines (Fig. 5.3). As it approached the Pennines the frontal rain was dying out but, subsequent forced uplift over the high ground triggered convective rainfall and produced rainfall totals in places in excess of 20 mm.

Figure 5.4 shows the storm total rainfall over the Upper Derwent for the period 0900-0300 hrs. The area of high rainfall is located in the west of the catchment over the high ground of Bleaklow with a steep gradient to the lower ground in the east. This apparently simple relationship between rainfall total and altitude is not maintained when the rainfall is analysed at 15 minute, or hourly intervals. As already discussed, the higher rainfall totals are not obtained by consistently higher rainfall intensities maintained throughout the duration of the storm but by localised bursts of intense rainfall. This event clearly illustrates this process.

The first localised burst occurred during the first hour of the storm and is most obvious at gauge C8 where 1.6 mm fell. At the two nearest gauges E14 and E15 only 0.1 mm and 0.7 mm respectively fell (Figure 5.4). For the next 5 hours rainfall intensities show a tendency to decrease in an

Figure 5.5 CORRELATIONS BETWEEN 15 MINUTE RAINFALL TOTALS AND ALTITUDE WITHIN 2KM RADIUS

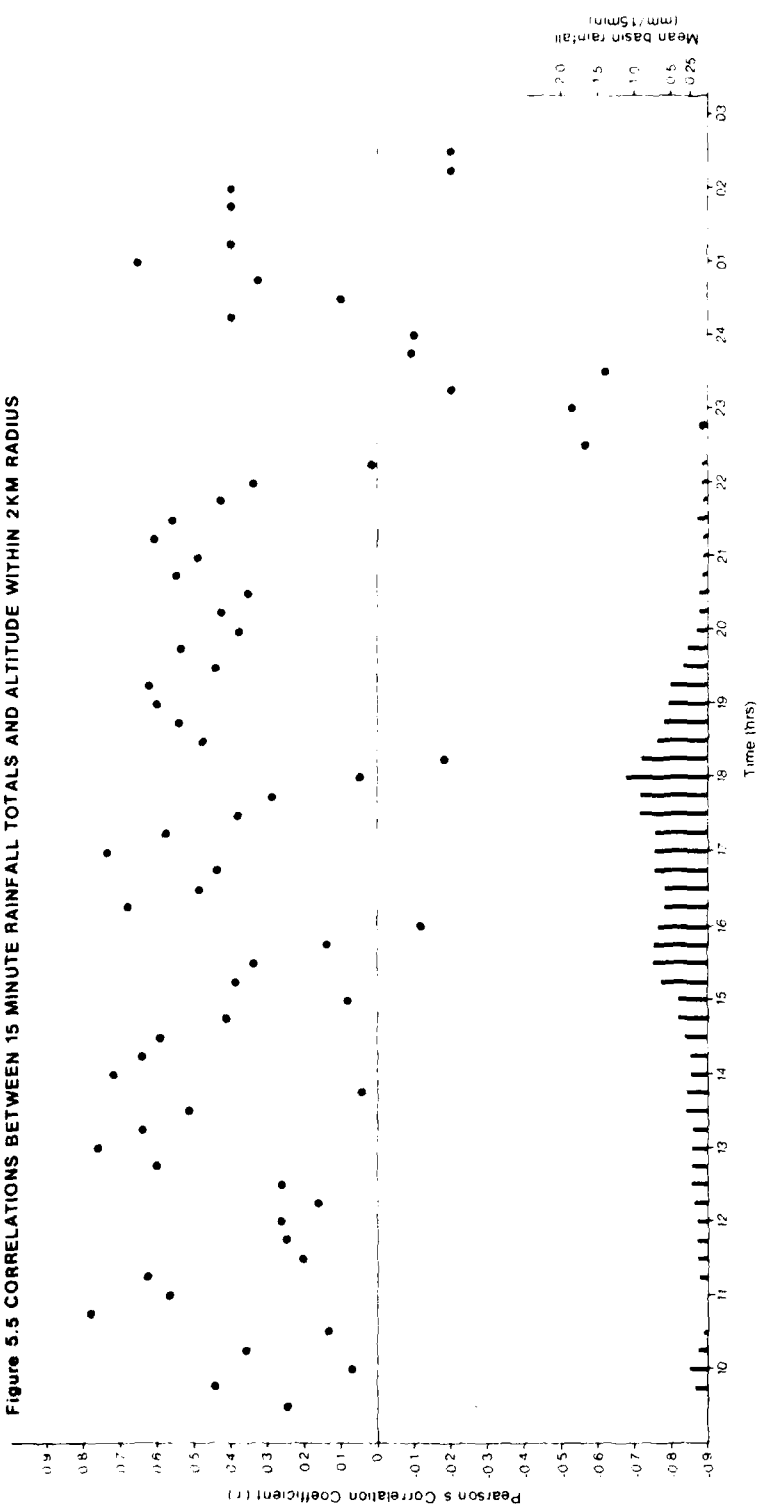


Figure 5.6 RELATIONSHIP BETWEEN RAINFALL (15 min totals) AND DISTANCE WEST TO DIVIDE

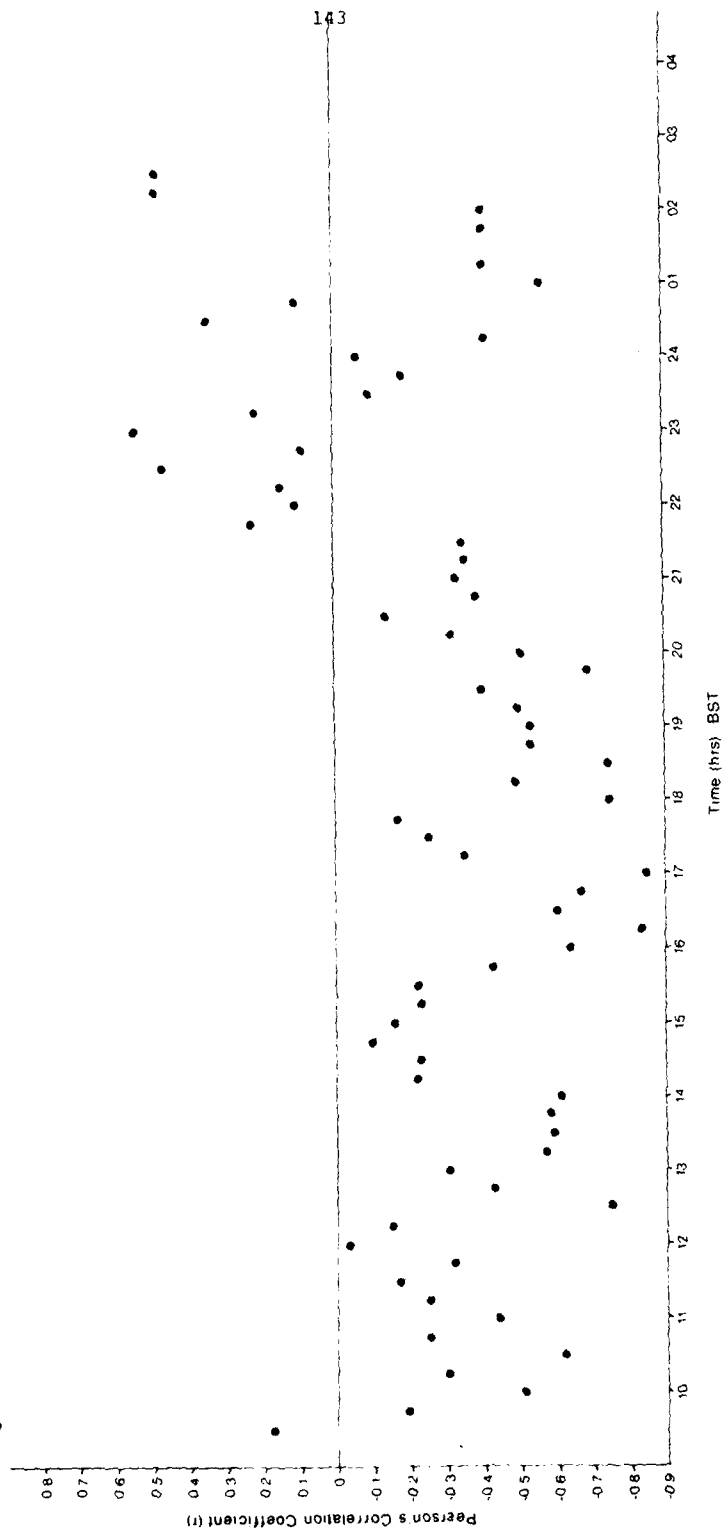
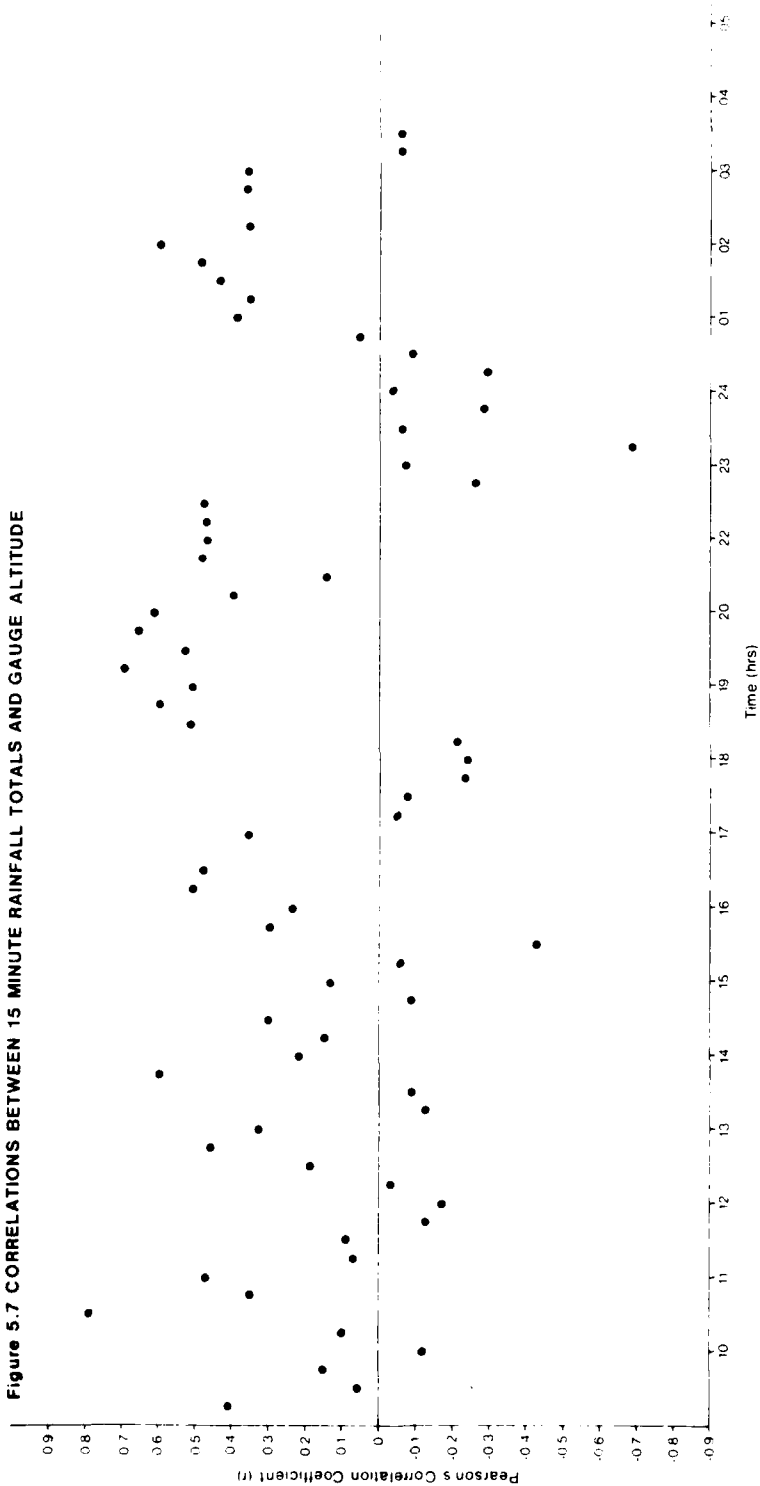


Figure 5.7 CORRELATIONS BETWEEN 15 MINUTE RAINFALL TOTALS AND GAUGE ALTITUDE



easterly direction. Between 1500 and 1600 hours another intense burst at gauge C8 produced an hourly rainfall total of 5.2 mm hour. At this stage gauge C8 had a cumulative total of 14.5 mm nearly three times that received at gauge A2. Three more significant bursts of high intensity rainfall occurred before the rainfall ceased. These are all apparent in the hyetographs of all the operating raingauges but most obviously so in the west of the catchment. The largest of these adds 6.5 mm and 5.2 mm to gauges C8 and E14. These two gauges are the nearest to the high ground of Bleaklow given the regional wind direction at the time.

Correlation analysis between hourly rainfall totals at the Upper Derwent sites and the topographic parameters produced generally low correlations (Table 5.5). The highest correlations occurred with those parameters depicting the location of high ground eg. altitude within 1 km and 2 km radius, distance west to divide and distance to Bleaklow; periodically these correlations were significant as discussed below. Where the hyetographs are analysed at 15 minute intervals and correlated with these three parameters varying degrees of periodicity are apparent in the correlation coefficients through time. This is most obviously so with "altitude within 2 km radius" (Figure 5.5) but is also apparent with "distance west to divide" (Fig. 5.6). If, however, gauge altitude is substituted (Fig. 5.7) very little periodicity is evident suggesting that the process causing this periodicity is not influenced by such localised topography. It is possible that these temporal correlations are showing up high intensity raincells moving across the catchment and that as they pass over the area they alter the resultant correlations; significant positive correlations occur when cells are over the western high ground, and vice versa. However, many more case studies would be necessary to confirm this hypothesis.

(9 gauge sites)
(A1, A2, C8, C9, D10, D11,)
(F12, E14, E15)

Table 5.5

Correlation Matrix for 16 August 1983. Hourly rainfall totals: Upper Derwent Catchment

Hourly ending:		10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	01	02
North		0.17	0.50	0.44	0.30	0.17	0.32	-0.09	0.27	-0.04	0.19	0.40	0.54	0.83	-0.42	-0.39	0.11	-0.33
East		-0.47	-0.87	-0.40	-0.63	-0.93	-0.39	-0.47	-0.88	-0.83	-0.85	-0.68	-0.54	-0.69	0.76	0.23	-0.37	-0.32
Altitude		0.20	0.38	0.24	0.14	0.16	0.20	0.04	0.47	-0.20	0.15	0.65	0.36	0.39	-0.29	0.34	0.60	0.36
Slope Angle		0.29	0.06	0.82	0.47	0.36	0.76	0.27	0.20	0.50	-0.02	-0.06	0.18	0.89	-0.49	-0.89	-0.39	-0.48
Sine Angle		0.37	0.25	-0.09	0.34	0.16	-0.06	0.34	-0.02	0.23	0.17	-0.05	-0.28	-0.14	0.03	0.62	0.71	0.64
Cosine Angle		-0.63	0.39	-0.08	-0.44	-0.07	-0.21	-0.54	0.42	-0.38	0.37	0.64	0.64	0.32	0.01	0.12	0.49	0.10
Distance to Divide		-0.07	-0.36	0.02	-0.02	-0.14	0.04	-0.02	-0.51	0.24	-0.29	-0.63	-0.28	-0.08	-0.11	-0.51	-0.62	-0.42
Distance West to Divide		-0.35	-0.62	-0.12	-0.45	-0.84	-0.19	-0.48	-0.83	-0.49	-0.81	-0.51	-0.30	-0.18	0.33	0.08	-0.23	-0.42
Altitude Within 1 Km Radius		0.50	0.69	0.40	0.56	0.50	0.40	0.28	0.56	0.19	0.37	0.47	0.36	0.58	-0.78	-0.05	0.63	0.54
Altitude Within 2 Km Radius		0.44	0.78	0.55	0.54	0.65	0.51	0.29	0.65	0.33	0.48	0.53	0.46	0.65	-0.89	-0.08	0.52	0.41
Sine Direction of Highest Ground (1 Km)		0.21	-0.14	0.07	0.27	0.14	0.10	0.42	-0.17	0.52	-0.01	-0.47	-0.57	-0.19	0.24	0.38	0.47	0.60
Distance to Bleaklow		-0.49	-0.86	-0.37	-0.63	-0.93	-0.38	-0.49	-0.87	-0.54	-0.84	-0.65	-0.49	-0.62	0.76	0.17	-0.42	-0.41
Sine Direction of Highest grid (2 Km)		0.19	-0.60	-0.08	0.02	-0.45	-0.02	0.14	-0.50	-0.12	-0.60	-0.52	-0.65	-0.39	0.72	0.25	-0.08	0.01

Correlation is significant at the 1% level if $r > 0.765$
Correlation is significant at the 5% level if $r > 0.632$

Figure 5.4 HOURLY RAINFALL 16.8.83

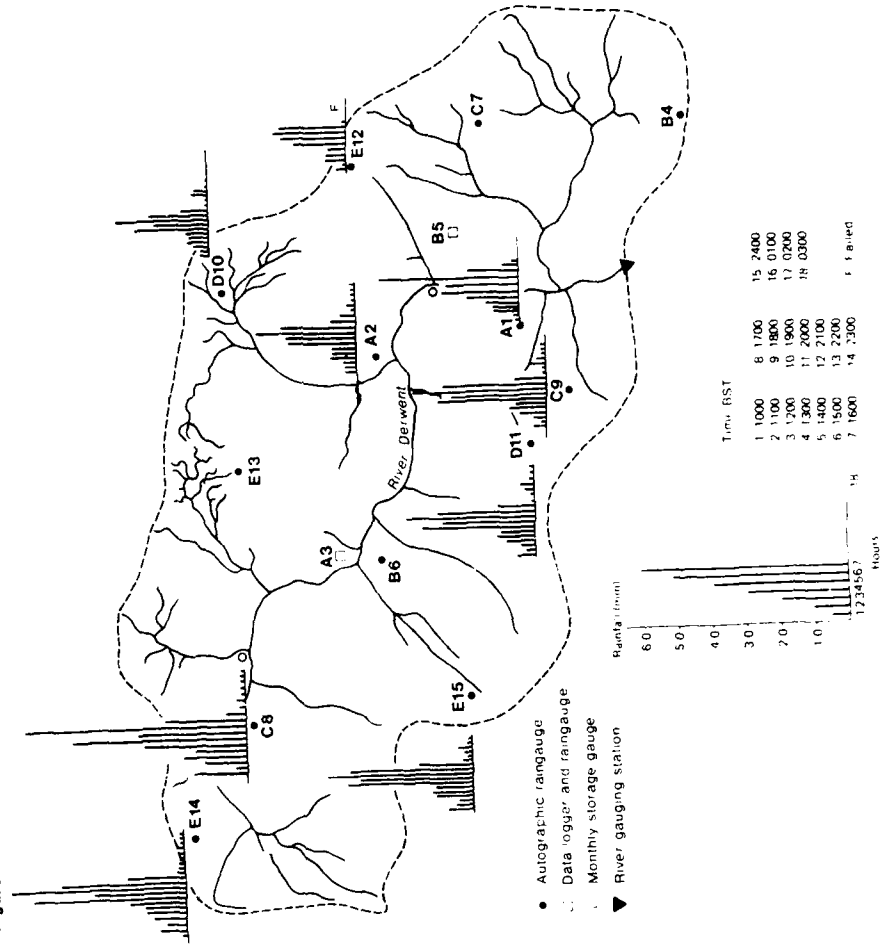


Figure 5.8 displays the relationship between storm totals over the entire southern Pennine study area and two of the gauges within the Upper Derwent catchment. The area of maximum rainfall is to the north and east of the Pennines, triggered by the fronts crossing the high ground in its path. Totals rapidly decline to the east and particularly to the south. Despite the difficulty of relating storm rainfall to topography within the Upper Derwent catchment, there is a clear relationship between storm totals on the two scales. Thus on this occasion, storm totals within the Derwent catchment reflect the broad band over the southern Pennines.

On an hourly time scale, intense bursts of rainfall cannot easily be traced across the Pennines even when wind spread and direction are taken into account. This is to be expected given the local nature of the rain cells and the apparently rapid growth and decay of such cells as seen earlier within the Upper Derwent. Figure 5.19 provides a breakdown of the storm into hourly intervals for three sites; Rivelin to the south, E14 within the Upper Derwent and Bury to the north west. A burst of high intensity rainfall at 1600 hrs at Bury is evident and is probably identical to a similar one an hour later at E14. The three hyetographs also illustrate the growth and decay of the storm as it moves south to Rivelin.

This case study illustrates the complex nature of hourly rainfall and the importance of localised intense bursts of rainfall in establishing the resultant storm total rainfall distribution.

Figure 5.9 RAINFALL HYDROGRAPHS FOR SELECTED SITES, 16.8.83

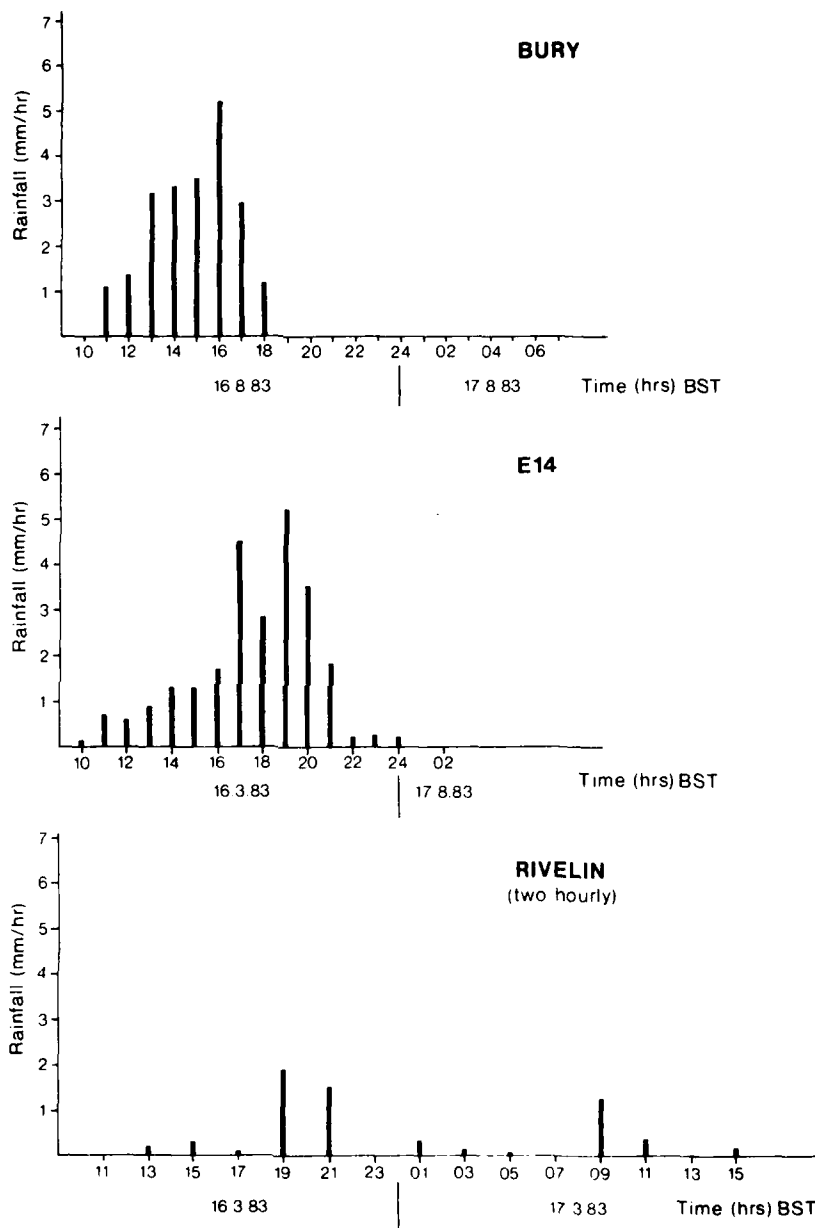
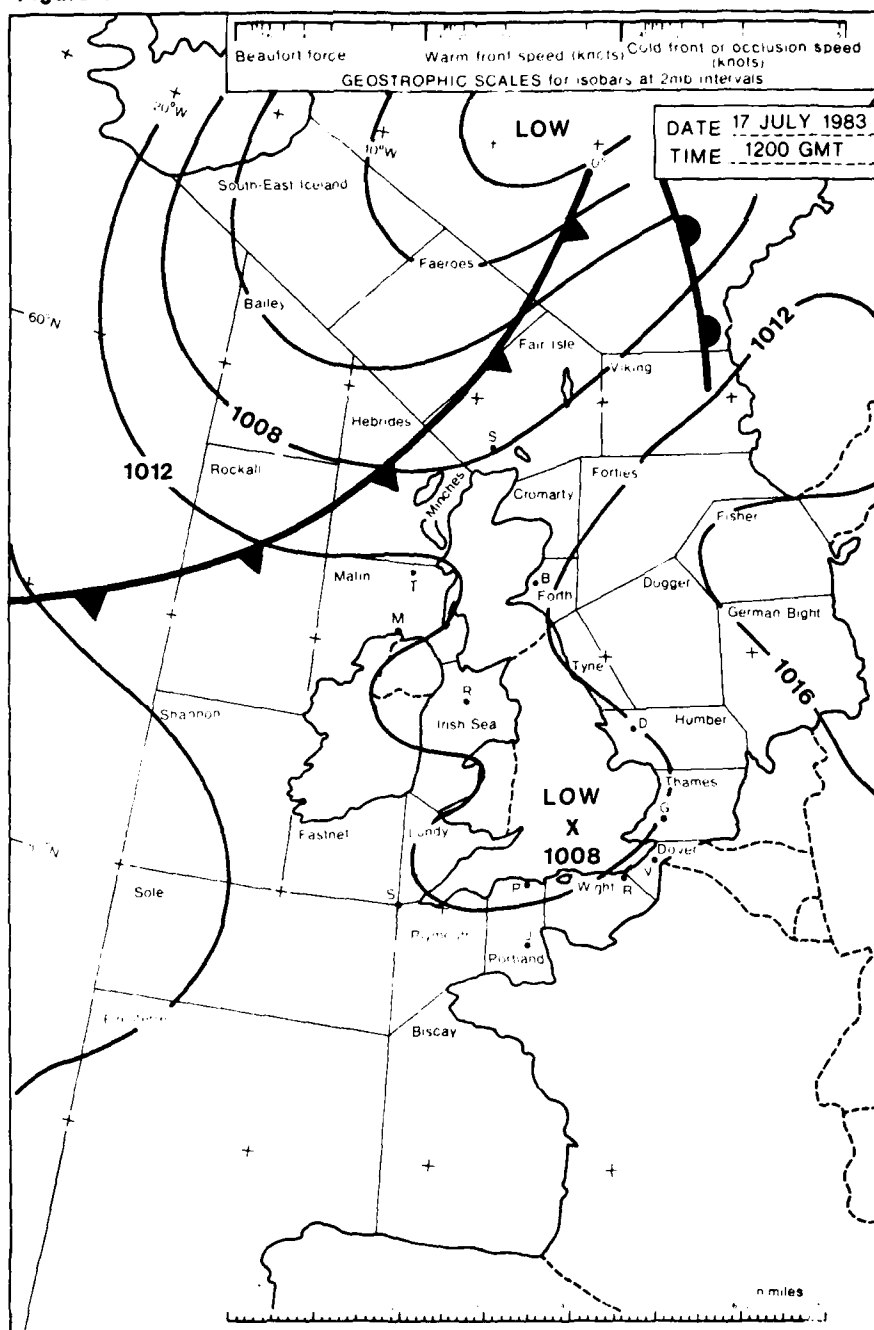


Figure 5.10 SYNOPTIC CHART FOR 17.7.83



Redrawn from Meteorological Office Material.

Case Study: 17.7.83

Localised thunderstorms:

Localised convective storms probably offer the greatest chances of a highly variable rainfall pattern. Two very localised storms occurred on the 17.7.83 starting at 0230 hrs and the second at 1400 hrs (BST). It is likely that both events relate to the same synoptic conditions as they are very similar in rainfall distribution though not in total. The synoptic chart (Fig. 5.10) shows a thermal low over England, a typical situation within which thunderstorms occur.

First storm event 0230-0330 hrs.

The first storm had a basin mean rainfall of only 1.4 mm ranging from 3.6 mm at C8 to 0 mm rainfall at C7. Wind speed was 5 Kt dropping to 2 Kt at 0300 and returning to 5 Kt during the period of rainfall and maintaining a direction of 90°. Storm development and movement was as follows:

- a) 0230-0245 hrs (BST). Precipitation started at 0230 hrs in the north west of the catchment with 0.3 mm at site E14 and none over the rest of the catchment.
- b) 0245-0300 hrs. Rainfall intensity increased in the upper catchment with a total of 0.8 mm at E14 extending along the NW ridge to as far as D11. The lower sites to the north east still had no rainfall.
- c) 0300-0315 hrs. Still centred to the north west of the catchment low rainfall intensities extended to all gauges except those at the extreme south west and gauge E13. It appears that the steep scarp-face running NW-SE along the northern edge of the catchment was blocking its further extension.

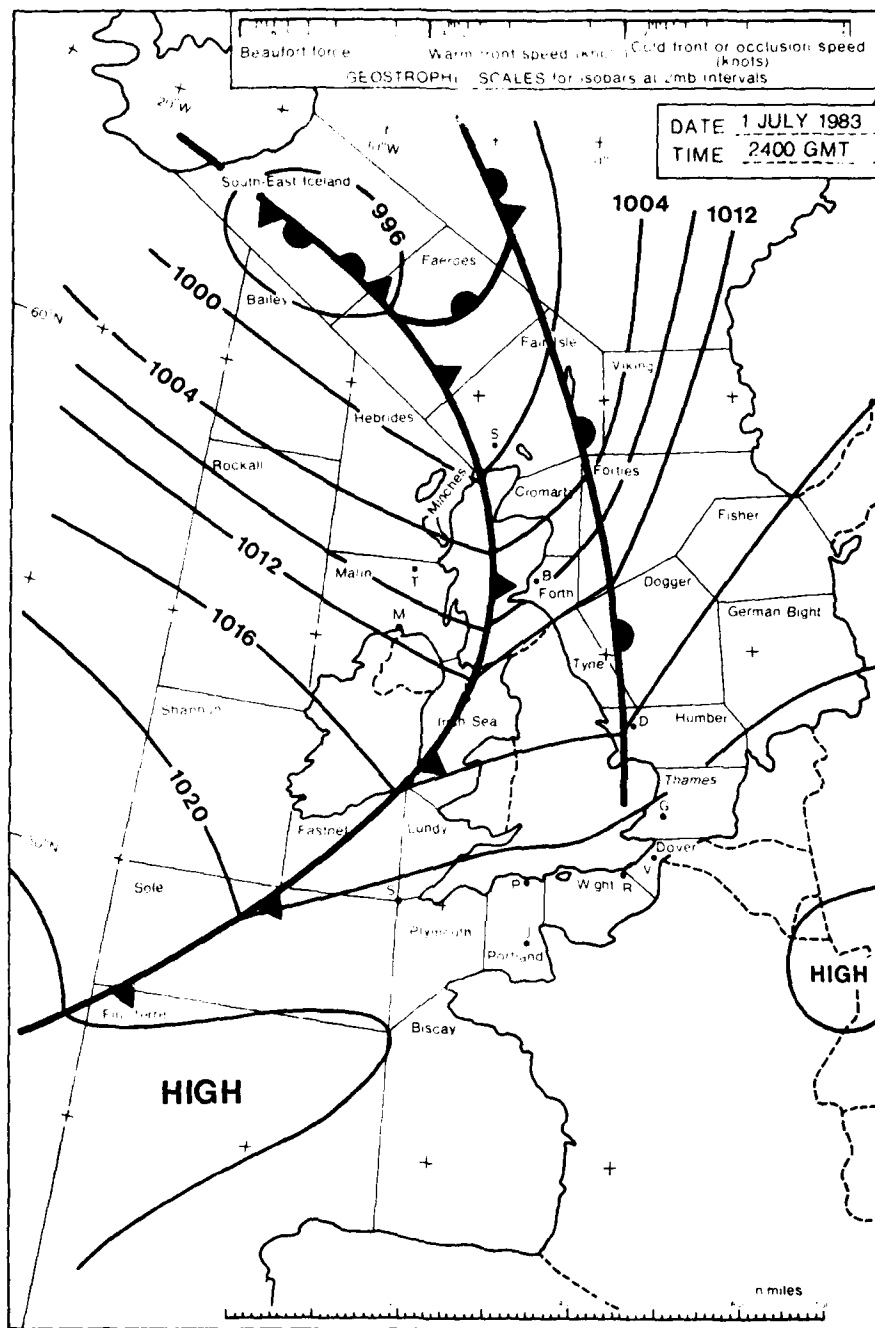
- d) 0315-0330. The storm centre shifted to the north east of the catchment with maximum 15 minutes total of 1.8 mm at E13 and the extreme west and east of the catchment having no rainfall.

Second storm event 1400-1515 hrs.

Mean basin rainfall for the entire period was 0.42 mm varying from 8.2 mm at E14 to 0.7 mm at C7 (Fig. 5.13). Wind speed fluctuated from 5 to 8 Kt; no wind direction data was available. The modal rainfall duration was 30 minutes but extended to 60 minutes and 65 minutes at sites E14 and E15 respectively. Both this and the previous storm were too localised to reach the data loggers in the wider network. Storm development and movement was as follows:

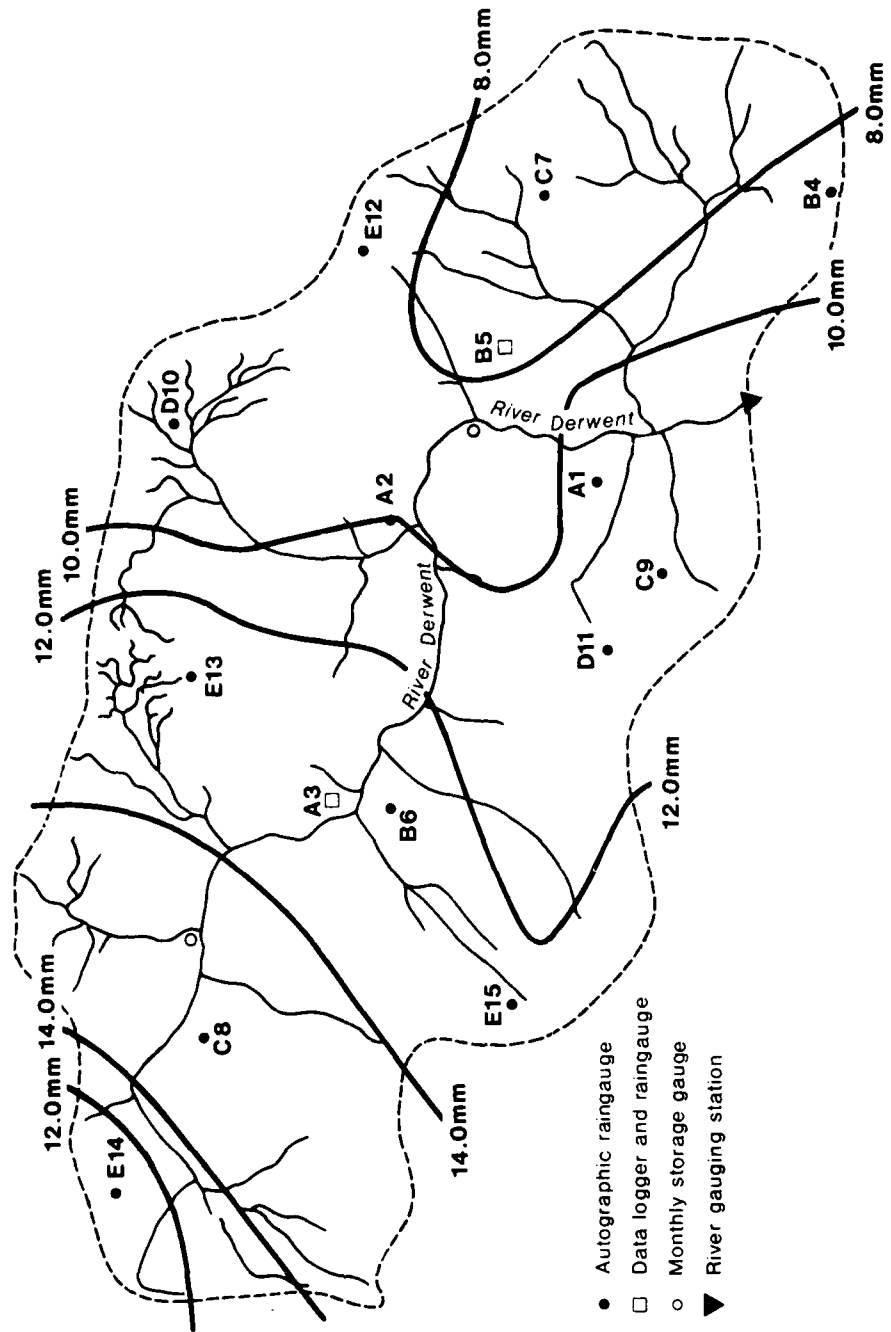
- a) 1400 hrs (BST). Only the NW of the catchment received rainfall with E15 catching 0.1 mm and E15, 2.8 mm. Most of this fell within about seven minutes as a very intense shower.
- b) 1400-1415 hrs. Rainfall extended further into the catchment but still with 75% of the area still receiving no rainfall.
- c) 1415-1430 hrs. A second very intense burst of rainfall occurred at at site E12 totalling 14.1 mm within about 15 minutes. The neighbouring gauge E15 caught only 0.2 mm and the remainder of the catchment stayed dry.
- d) 1430-1445 hrs. The storm centre shifted southwards and the intensity greatly reduced. Maximum rainfall for this period occurred at E15 (1.2 mm) quickly dropping to 0.1 mm to the east but extending further in a NW-SE orientation.
- e) 1445-1500 hrs. Still reducing in intensity to the centre of the storm moved further SE with maximum rainfall at site C9 (0.8 mm). Rainfall totals fell off quickly to the NW-SE but extended in a north-south direction.

Figure 5.12 SYNOPTIC CHART FOR 1.7.83



Redrawn from Meteorological Office Material.

Figure 5.13 TOTAL RAINFALL 1.7.83



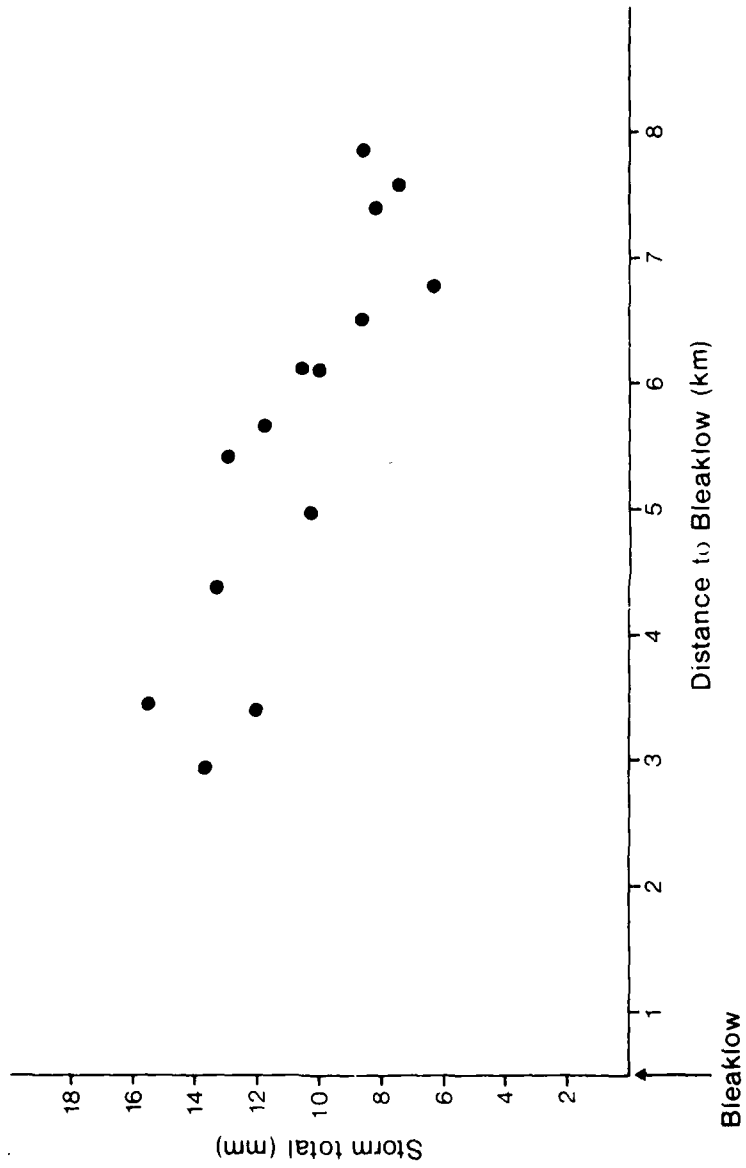
- f) 1500-1515 hrs. A final localised increased intensity at site C9 (2.2 mm) and to a lesser extent at E12 (0.5 mm). The remainder of the sites catch less than 0.2 mm.

These two rainfall events, one centred over the east ridge of Bleaklow and the second, later in the day, centred on the Longendale Valley illustrate the kind of rainfall distribution that can occur with convective cells. However, with convective rainfall the pattern of rainfall distribution is entirely unpredictable, once instability is triggered. Thus, if there is a high correlation between high ground and rainfall total this is purely incidental.

Case Study: 1.7.83

Rainfall occurred over the southern Pennines between 2000 hrs and 0600 hrs during the rainday 1.7.83 associated with weak warm and cold fronts (Fig. 5.12). Within the Upper Derwent catchment total rainfall varied from 7.6 mm in the east of the catchment (gauge C7) to 15.5 mm near Bleaklow (gauge C3) (Fig. 5.13). The rainfall intensities throughout the storm were consistently higher at those gauges to the north and west of the catchment. This can be illustrated by correlating gauge storm totals with each hourly total. Table 5.6 confirms that consistently higher hourly rainfall totals occurred over the high ground in the west. Only towards the end of the storm does the correlation between storm totals and hourly totals disappear and the system move away to the east. Note that little was contributed to the storm total during this period (0300-0500 hours).

Figure 5.14 STORM TOTAL (1.7.83) AGAINST DISTANCE TO BLEAKLOW
($r^2=61.5$)



The gauge totals to the west and north were further increased by two periods of much higher rainfall intensities. These occurred at hour ending 2220 hrs and for the three hours ending 0300 hours. To a limited extent these can be seen in the slightly higher correlations during these times in Table 5.6.

Table 5.6 Correlations between successive hourly rainfall totals and storm total rainfall

Time	Correlation
2000	0.79
2100	0.75
2200	0.76
2300	0.63
2400	0.68
0100	0.82
0200	0.80
0300	0.32
0400	0.49
0500	-0.22

Figure 5.15 contrasts the hyetographs of the two most extreme gauge catches and Figure 5.16 the three hour rainfall totals ending at 0300 hours for the Upper Derwent. The size and location of the area of most intense rainfall is clearly visible, centred on gauge C8.

Over the wider southern Pennine study area, maximum rainfall occurred over the highest plateau areas of Kinder Scout and Bleaklow just encroaching on the Upper Derwent catchment area (Fig. 5.17). Thus, this

Figure 5.16 STORM TOTAL FOR THE THREE HOURS ENDING AT 0300hrs 1.7.83

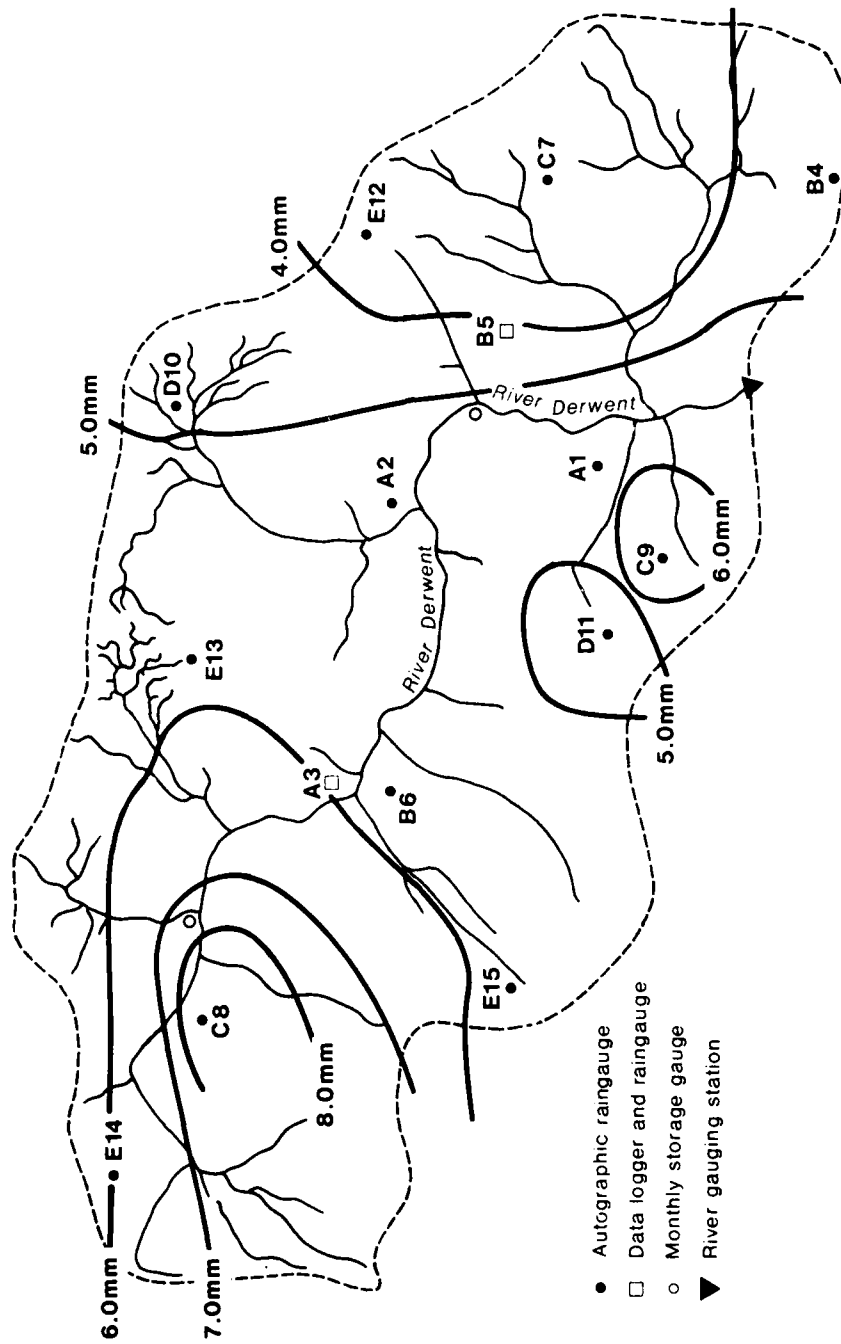
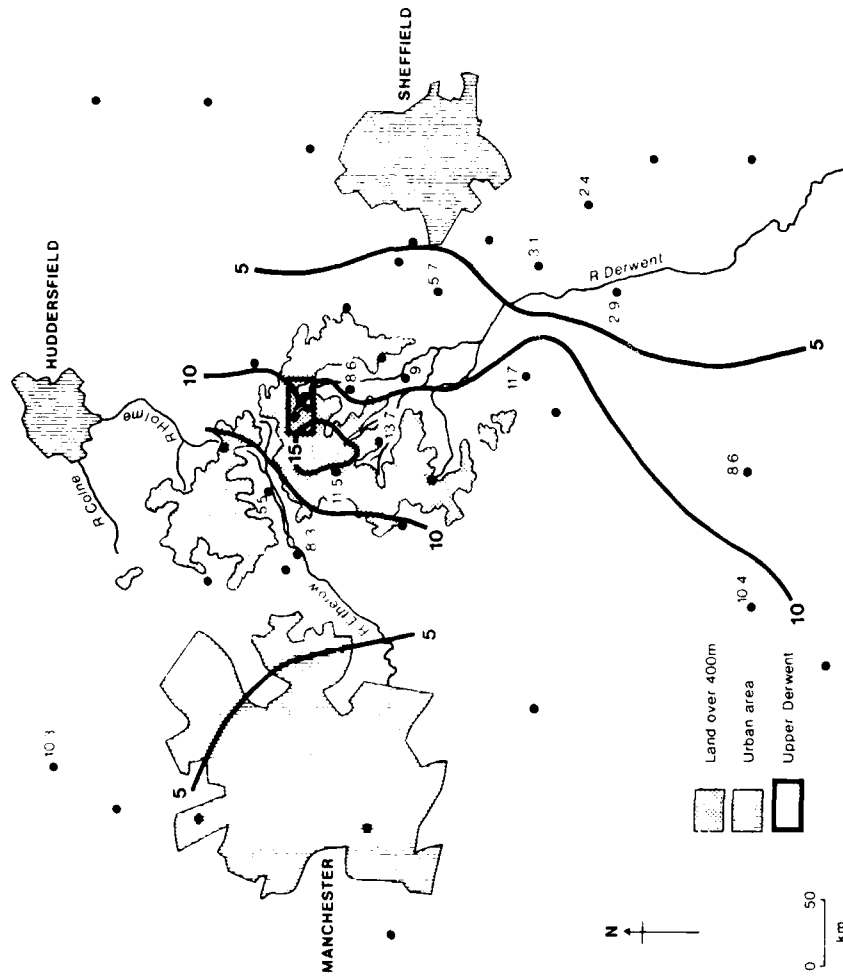


Figure 5.17 SOUTHERN PENNINE STORM TOTALS 1.7.83

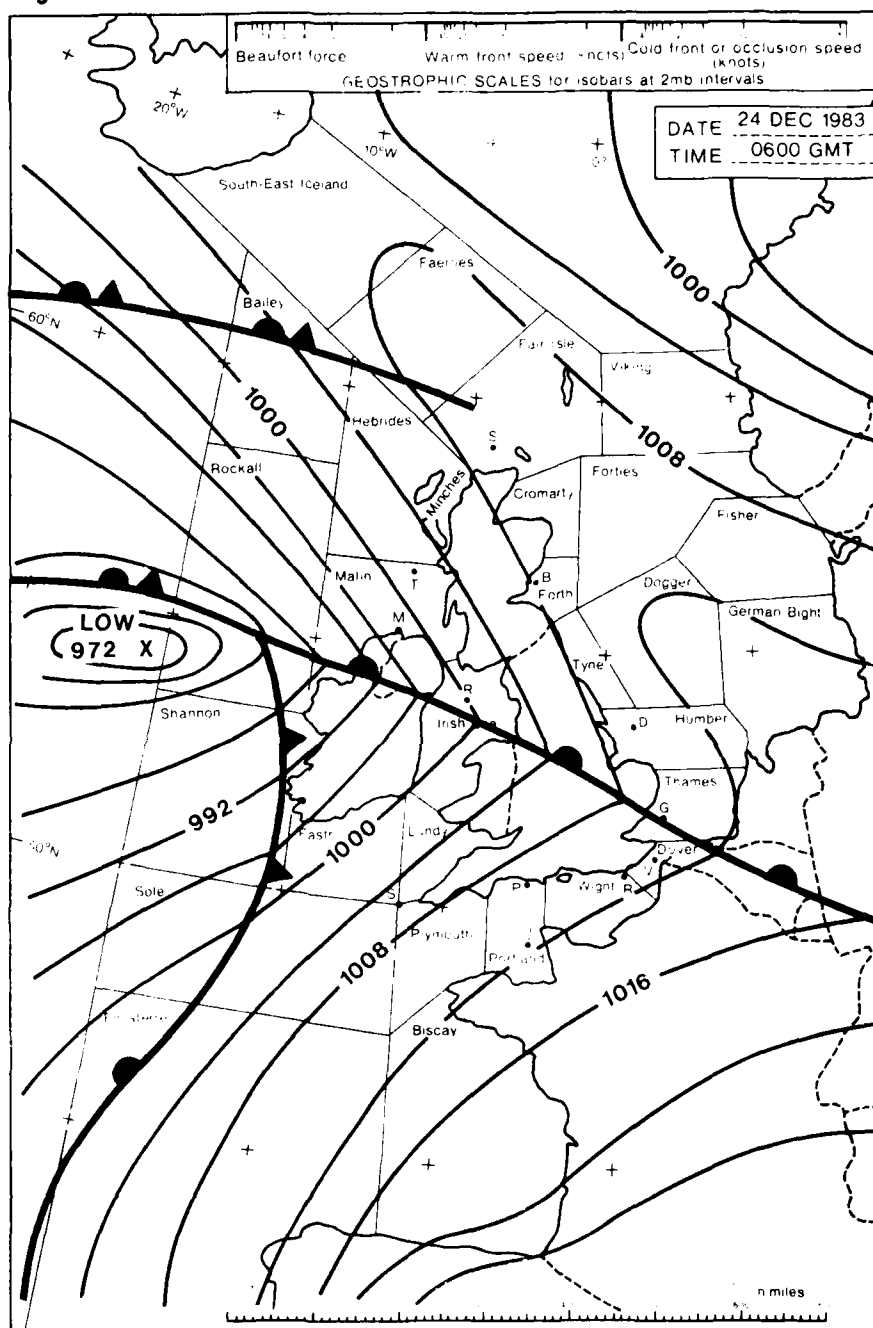


event appears to be a classic case of higher rainfall totals on the high ground. However, this cannot be attributed to "pure" orographic rainfall involving the feeder-seeder mechanism as convective rainfall was triggered and contributed to the storm total.

Events displaying 'pure' orographic enhancement

Perusal of radar scans for those events for which a good percentage of the Upper Derwent raingauges were operating showed that the orographic enhancement was always (in part or wholly) in the form of unstable convective raincells and not as a more general zone, devoid of raincells, covering the entire upland area. Only this latter pattern would imply 'pure' orographic enhancement involving feeder-seeder clouds, as discussed in Chapter 1. Three events at the end of 1983 were identified using radar as displaying a 'pure' orographic pattern. Although these events could only be studied using the three data loggers and the wider network of Water Authority raingauges, they are briefly considered here in order to complete our survey of upland rainfall events. Of course, since such 'pure' enhancement is apparently relatively rare (judging by radar) and even then only often occurs as part of an event (since some intense frontal rainfall unaffected by enhancement might also be involved), it is clear that much orographic rainfall must be convective in origin, supporting the early arguments of Bonacina (1945). It is likely, however, that the origins of the enhancement can only be determined by detailed within-storm analysis of the rainfall pattern, and not by simply mapping storm rainfall totals. Despite the random movement of individual rain cells, storm totals may still accord quite closely with altitude.

Figure 5.18 SYNOPTIC CHART FOR 24.12.83



Redrawn from Meteorological Office Material.

**Figure 5.19 RAINFALL HYDROGRAPHS FOR SELECTED SITES,
24.12.83**

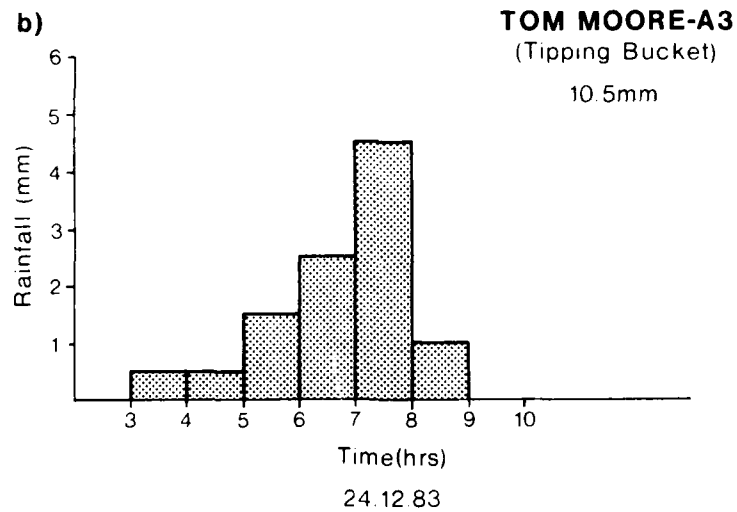
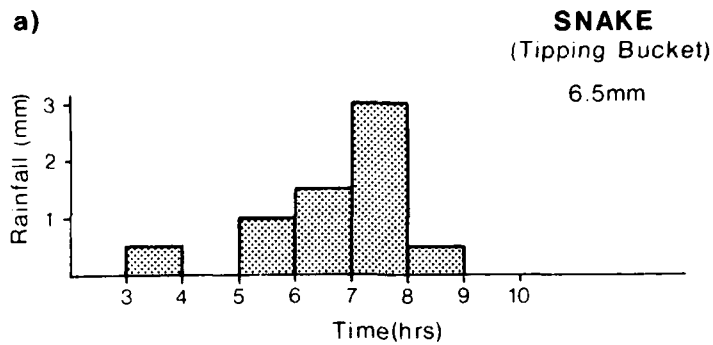
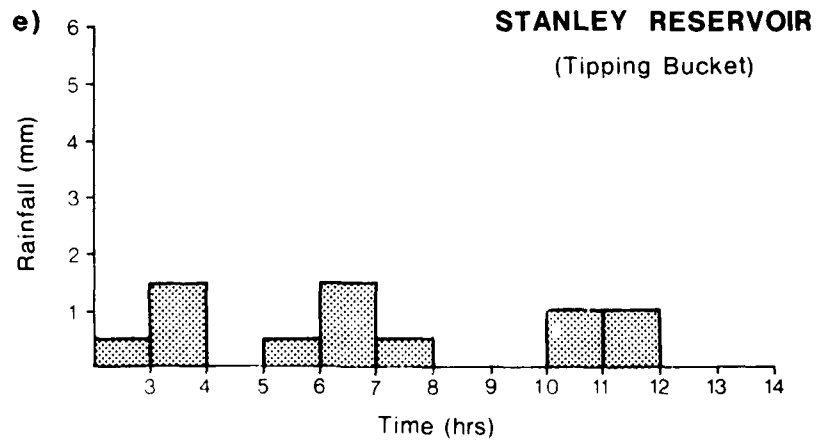
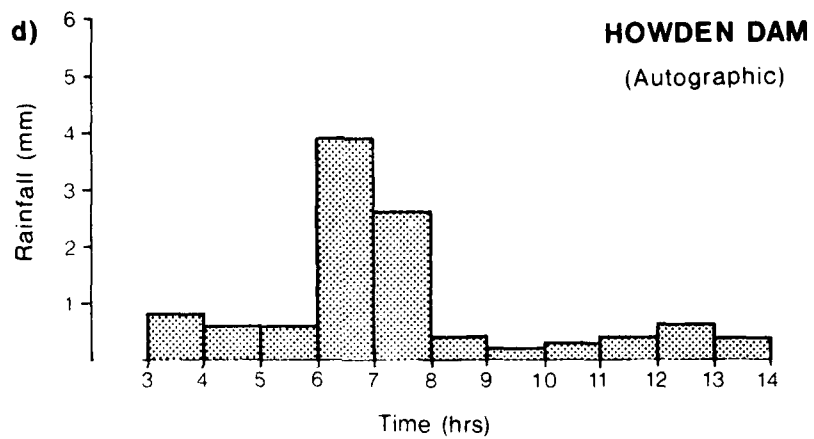
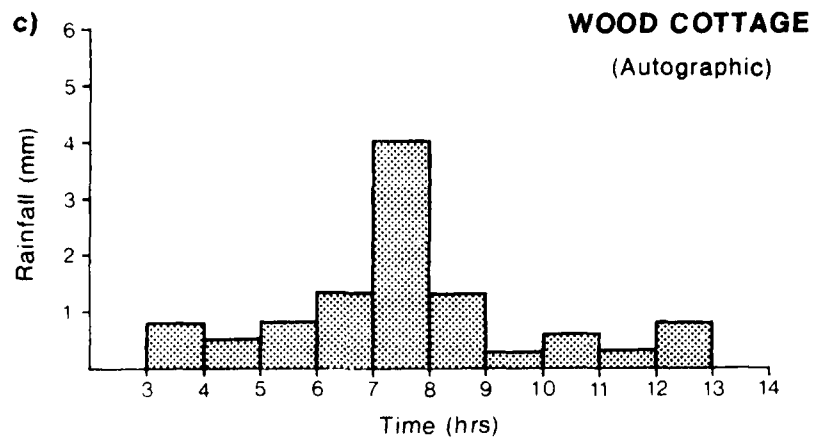


Figure 5.19 (cont)



24.12.83

Case Study: 24.12.83

The synoptic situation for 0600 GMT shows a warm front moving north-east over the southern Pennines (Fig. 5.18). Five rainfall hyetographs are presented on Figure 5.19; four (a-d) are for upland gauges, with Stanley Reservoir (e) being representative of an upwind, lowland location. Radar indicated a general zone of enhancement over the Pennines, particularly as the warm front approached: compared to Stanley Reservoir, enhancements of 3 mm hr^{-1} are evident at this time. Note that enhancement is less at Snake Pass, right on the western escarpment, perhaps because of the generally SW-NE track of the front which would have moved over the high ground of Kinder Scout (600 m) before reaching the Upper Derwent area. It may also be that relatively high winds (force 4) caused the feeder clouds to develop downwind of the escarpment edge, a feature also noted by Hill et al (1981) in South Wales.

Case Study: 25.12.83

The synoptic chart (Fig. 5.20) shows an occluded front moving west to east, causing rainfall over the southern Pennines early on 26.12.83 (by convention in the UK this counts as part of the 25.12.83 rainday which runs to 0900 hrs, 26.12.83). Once again high winds, of force 4 or 5 at the time that the front passed through, carried the main enhancement to the east of the highest ground at the western escarpment. This is confirmed both by the regional map of rainfall day totals (Fig. 5.21) and by examination of individual rain gauge hyetographs (Fig. 5.22). The enhancement is shown by comparing the records at Bury (b) and Stanley Reservoir (d), both lowland gauges in the west, with the records at Greenfield (a) and Snake (c), both at the escarpment, and with Tom Moore (A3-c), further to the east. Once again, enhancement is up to

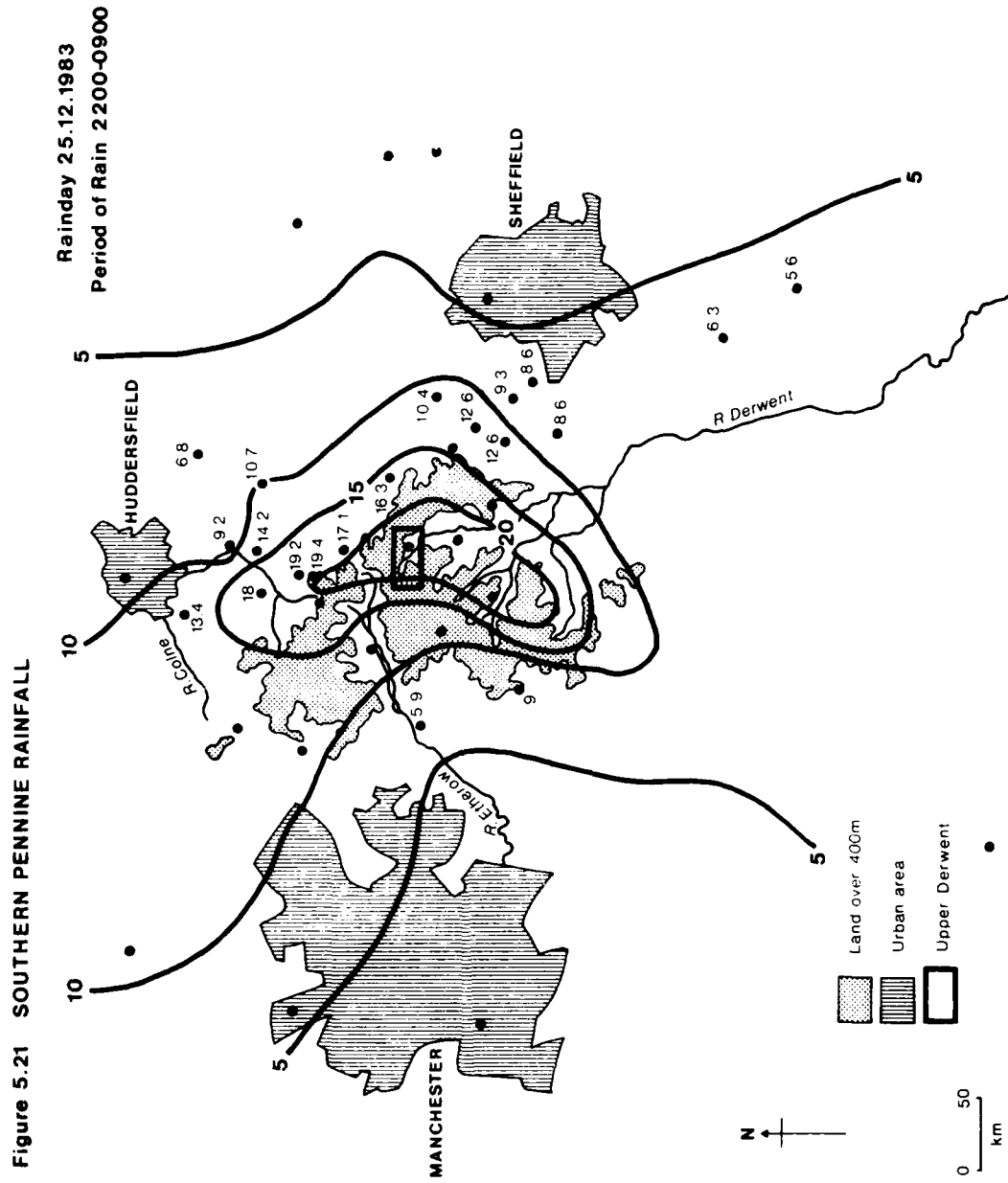


Figure 5.2.2 RAINFALL HYDROGRAPHS FOR SELECTED SITES, 25.12.83

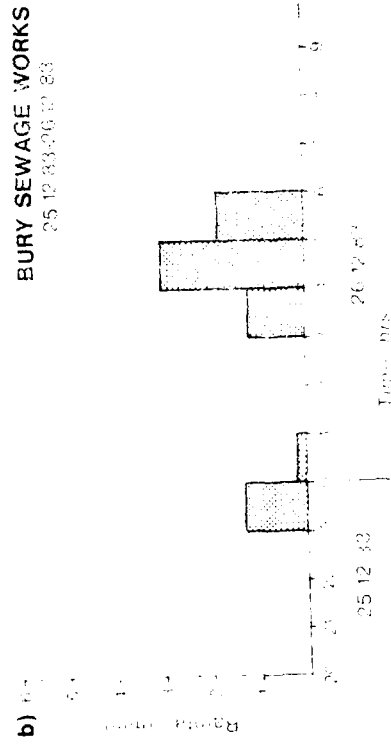
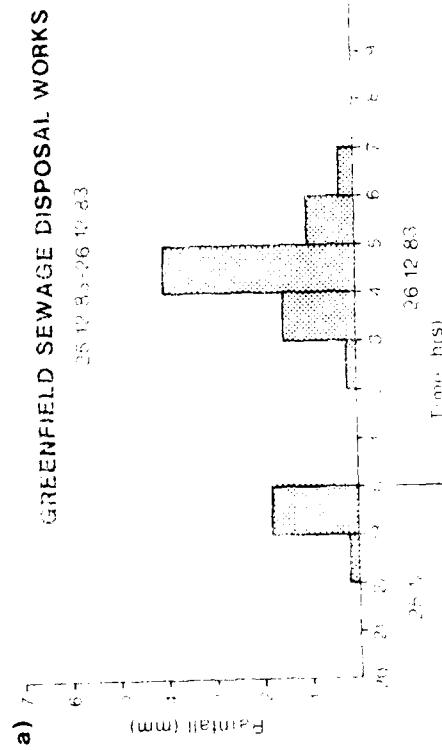


Figure 5.22 (cont)

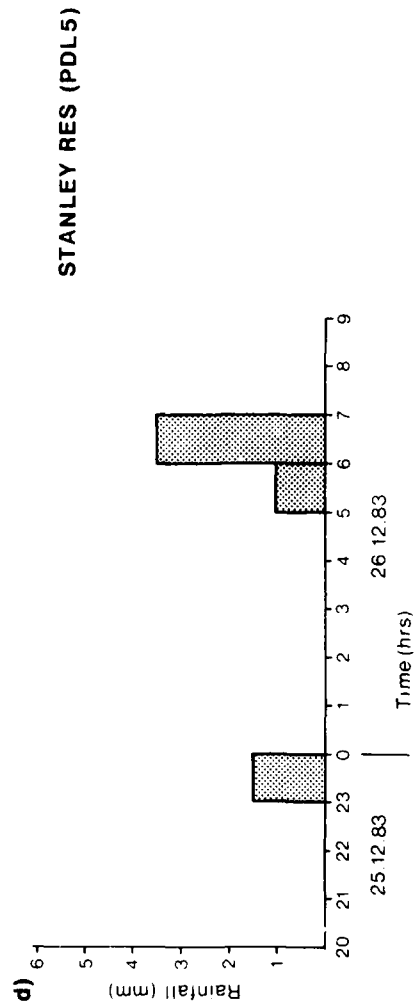
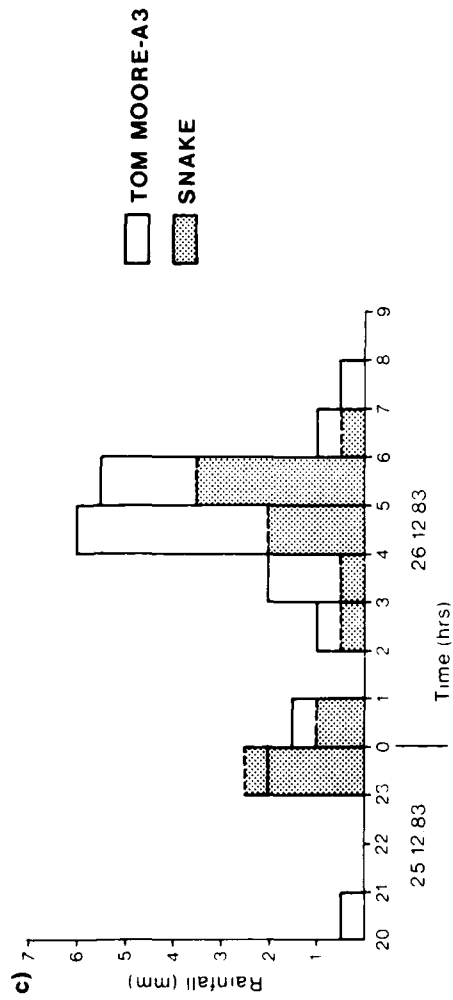
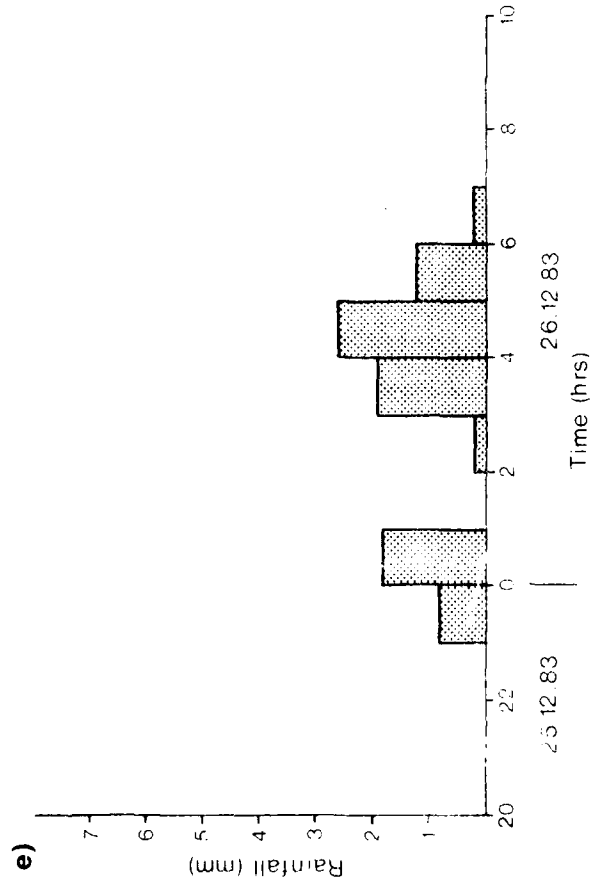


Figure 5.22 (cont)

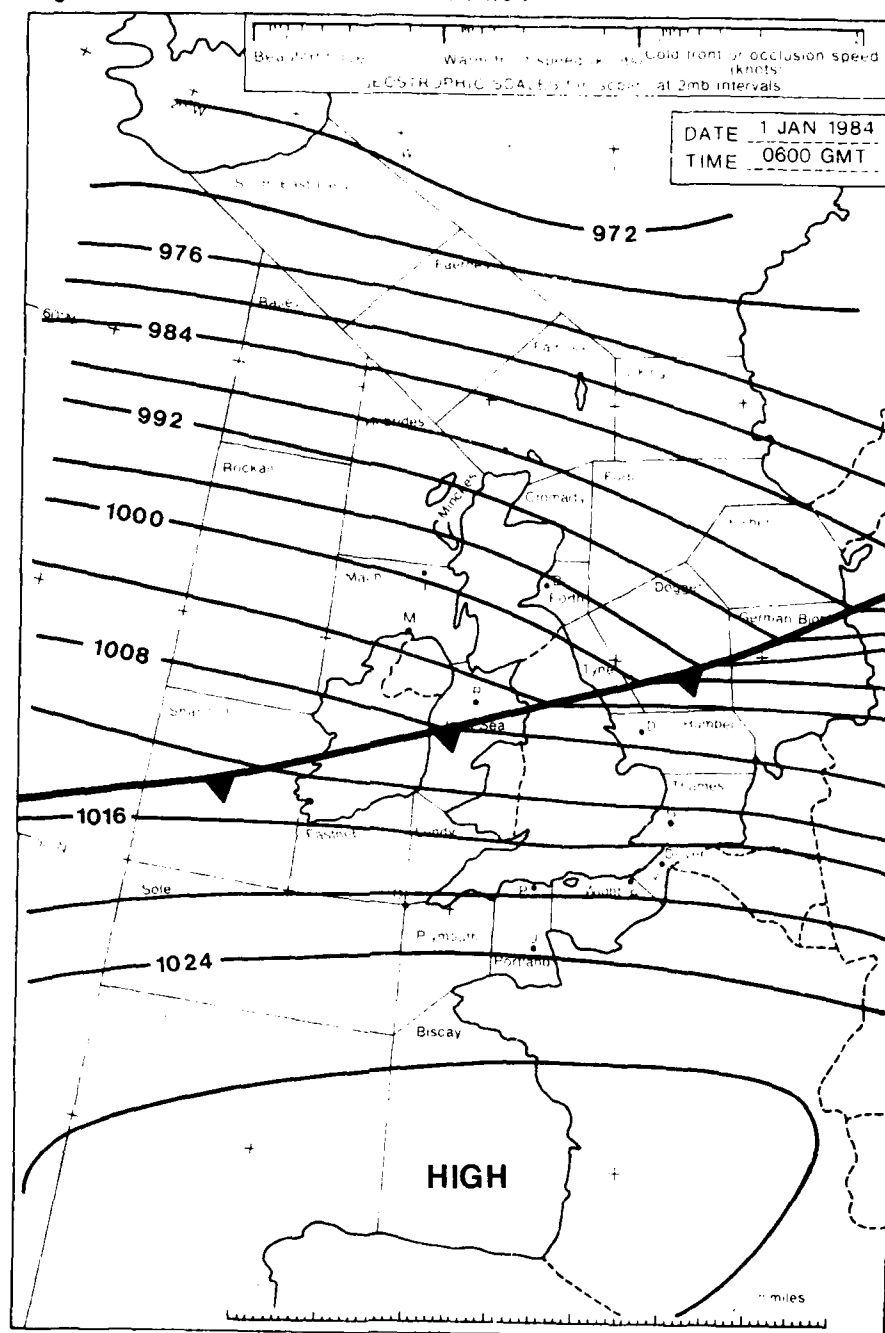


3 mm hr⁻¹. To the east of the enhancement zone, the descending air mass clearly precludes the occurrence of high rainfall intensities, as noted at Naden, near Sheffield (e). During the main period of rainfall between 0400 and 0600, Tom Moore (A3) received a total of 11.5 mm compared to 5.5 mm at Snake Pass, and 3.6 mm at Naden; at Stanley reservoir, if one allows for apparent differences in the timing of rainfall, the equivalent total is 4.5 mm. It is also notable that total rainfall in the surrounding lowlands is below 5 mm, but rises to 20 mm at Tom Moore and 22.7 mm at Wood Cottage, suggesting that 'pure' orographic enhancement can be responsible for large differences in rainfall total between the lowlands and uplands, perhaps up to four times. Burt (1980) noted similar rates of enhancement for storms in this area. The rainfall gradient with altitude is further confirmed using the data on Table 5.7. The regression equation predicts a 3.5 mm increase in rainfall for every 100 metres gain in altitude. The correlation of $r = 0.695$ is significant at the 0.01 level, and would perhaps have been stronger had there not been the 'lag' effect noted above; thus rainfall at Snake Pass (518 m) was much less than predicted by the regression. There was also evidence that the regression underestimated totals in the altitude range 260-390 m, which suggests a curvilinear relationship between rainfall and altitude with marked enhancement over the higher ground; note that almost all the upland gauges lie in this altitudinal range.

Case Study: 1.1.84

The synoptic chart (Fig. 5.23) shows a trailing cold front lying over northern England, which moved gradually south-east during the day. It is clear from the Meteorological Office description of 'occasional rain' and from the hyetographs such as Stoake Pollution Control works that rainfall

Figure 5.23 SYNOPTIC CHART FOR 1.1.84



Redrawn from Meteorological Office Material.

Figure 5.24 RAINFALL HYDROGRAPHS FOR SELECTED SITES, 1.1.84

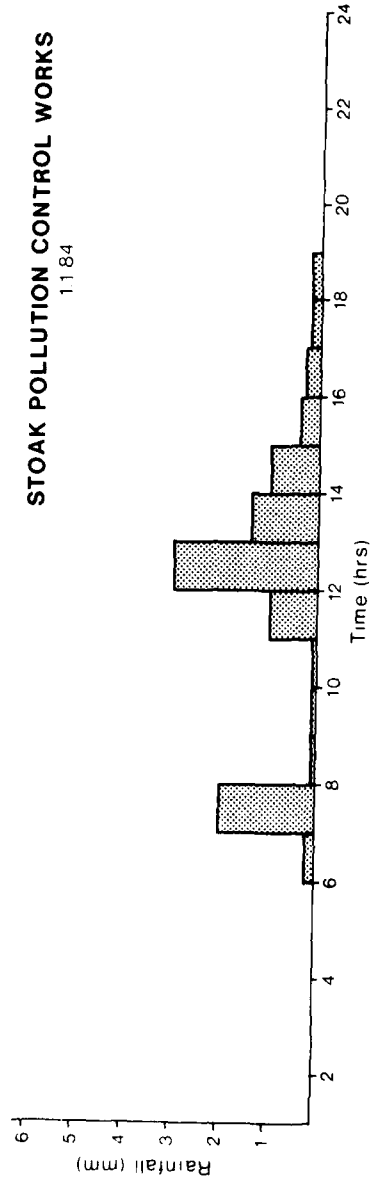
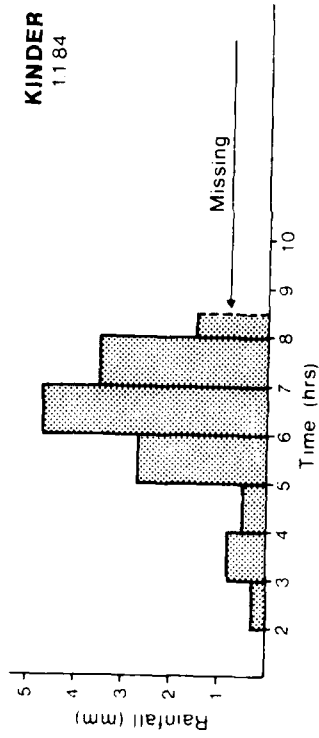


Figure 5.24 (cont)

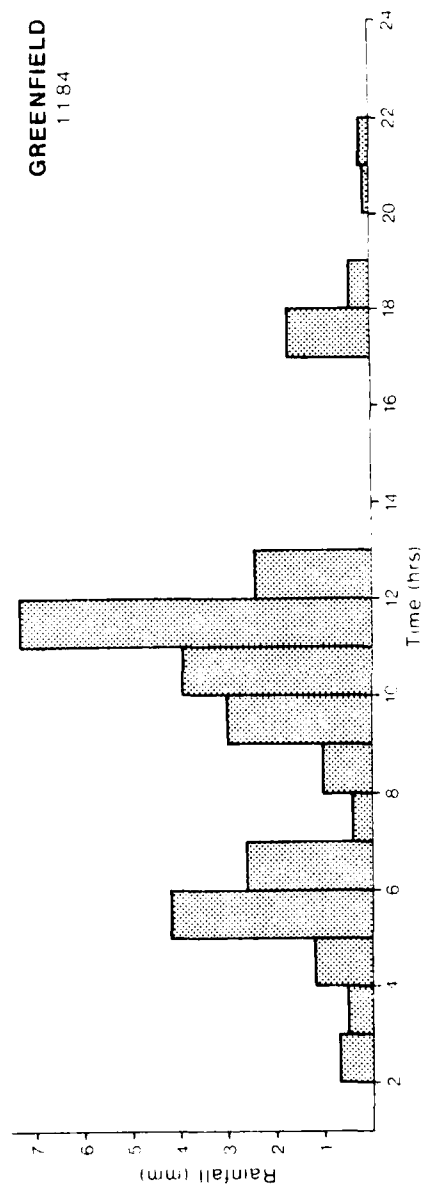
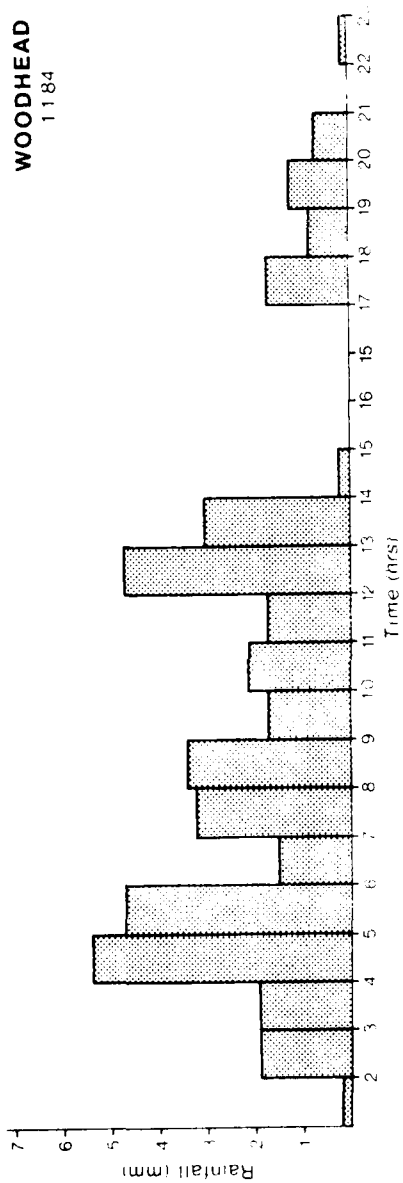


Figure 5.24 (cont)

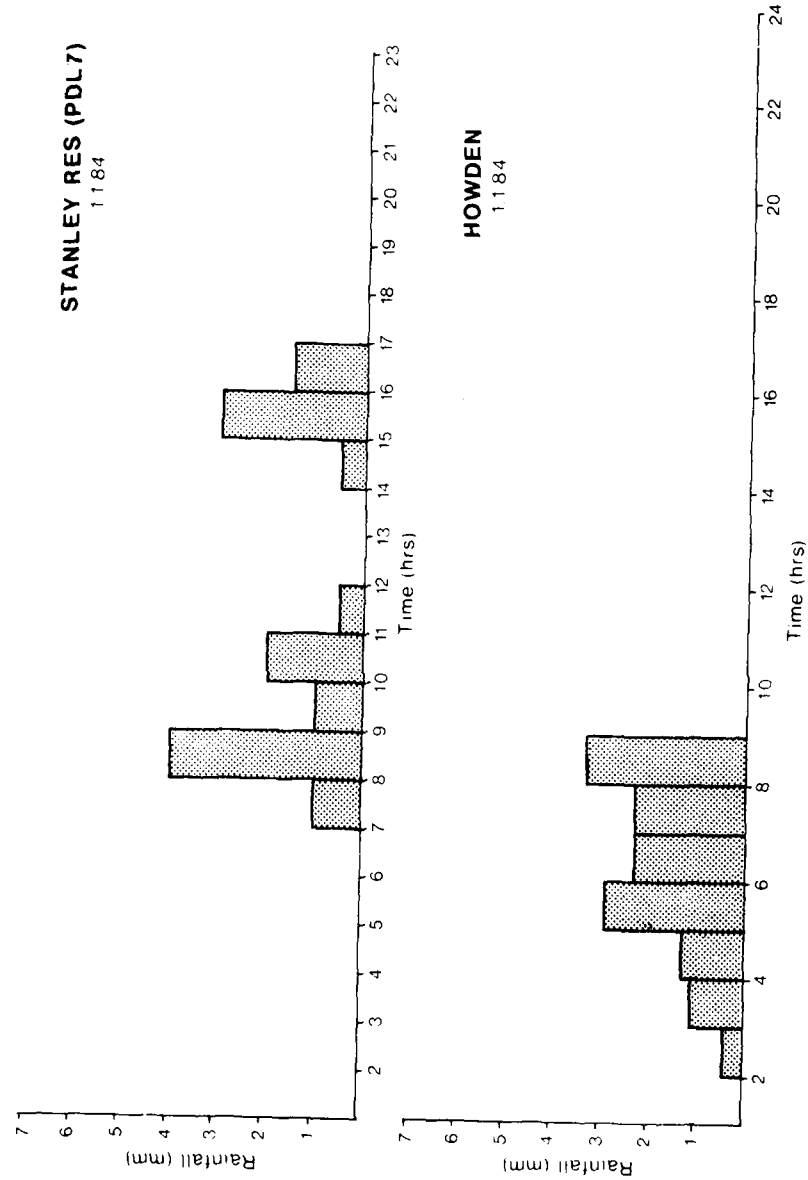


Figure 5.24 (cont)

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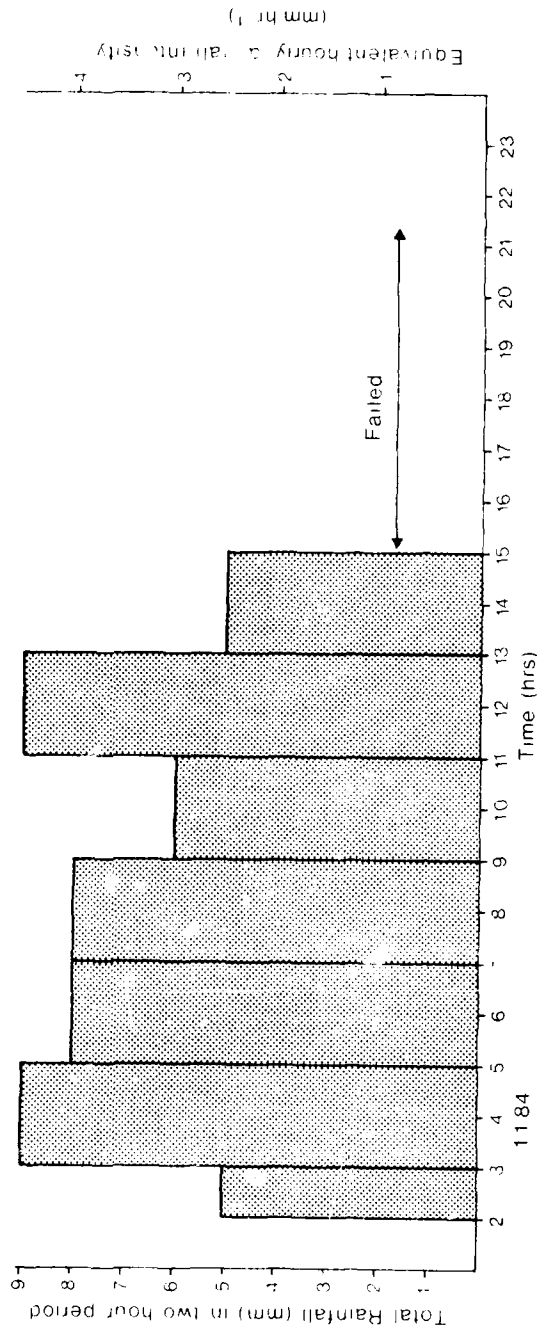


Figure 5.24 (cont)

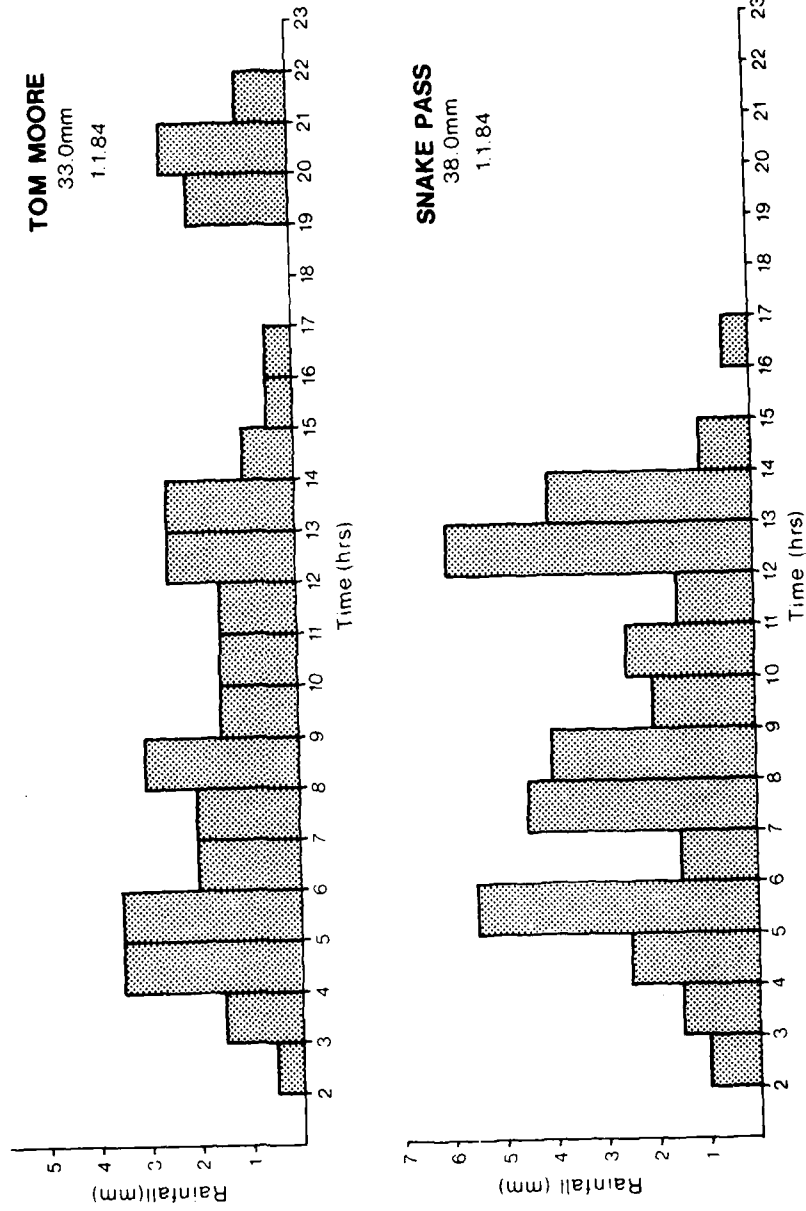


Figure 5.24 (cont)

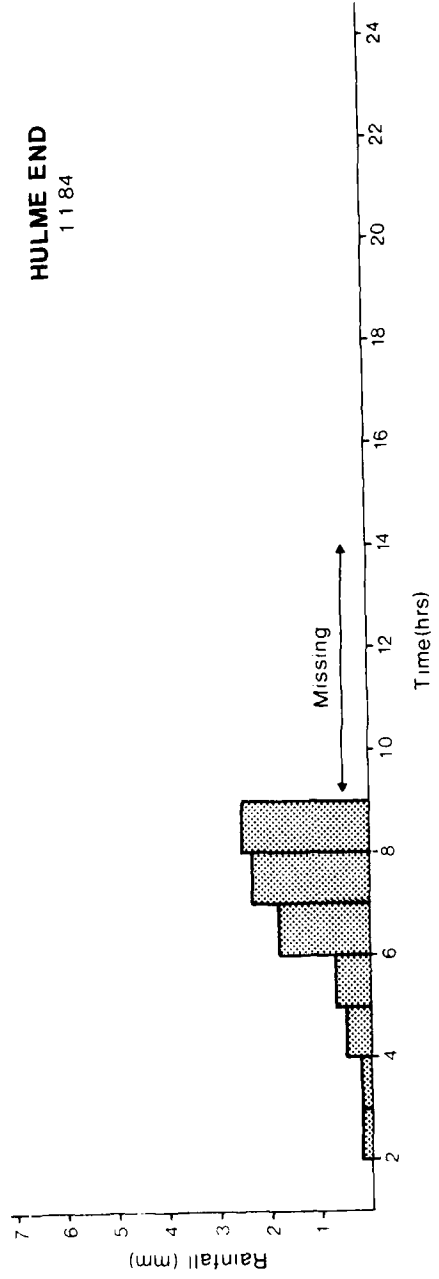
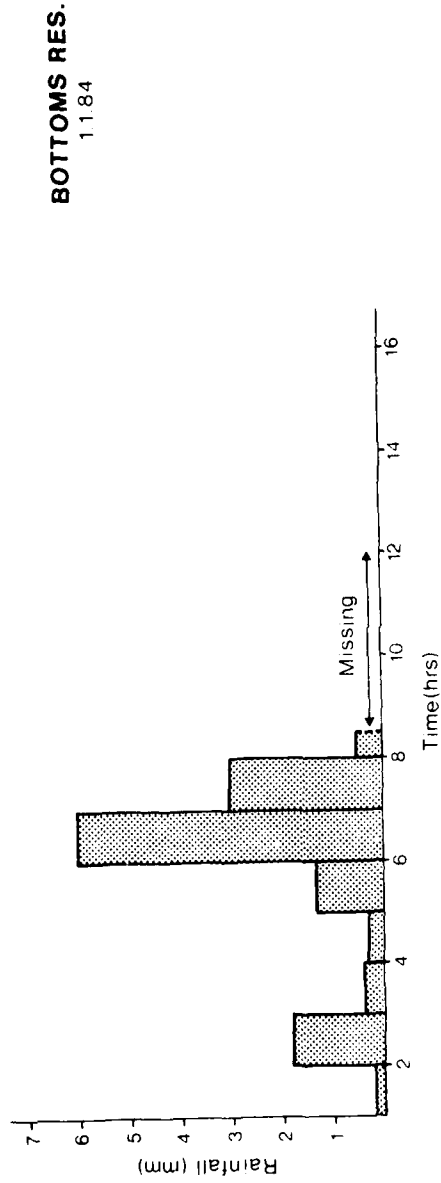


Figure 5.24 (cont)

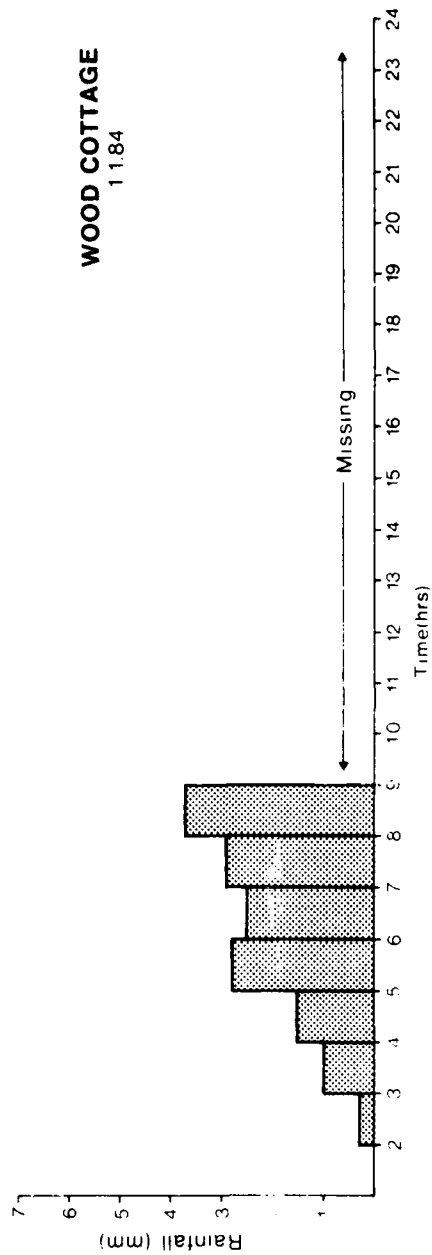
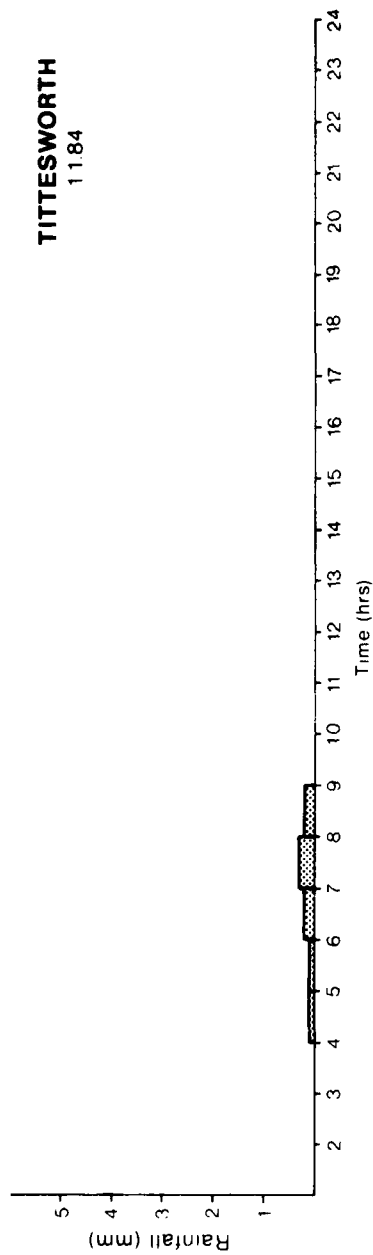


Table 5.7 Total rainfall at thirty three south Pennine gauges for the rainday 25 December 1983.

Gauge	Rainfall (mm)	Altitude (m)
Blackmoorfoot	13.4	244
Bobus	14.5	366
Digley	18.0	253
Holmestyes	14.2	262
Oakes	8.8	235
Neiley	9.2	107
Ramsden	19.2	262
Yateholme	19.4	308
Barnsley	3.5	40
Darfield	2.7	25
Emley	6.8	259
Blackburn Meadow	3.2	43
Bradfield Filters	12.6	168
Crookes	8.6	192
Ingbirchworth	10.7	260
Langsett	16.3	250
Mexborough	1.4	23
More Hall Reservoir	10.4	124
Redmires	8.6	305
Rivelin	9.3	172
Thrybergh	2.9	56
Thurlston Moor	17.2	271
Winscar	17.1	290
Linacre	6.3	159
Winger	5.6	126
Naden	10.6	230
Kinder Downfall	9.1	244
Greenfield	11.0	152
Wood Cottage	22.7	310
Bottoms Lodge	5.9	153
Stanley Reservoir	6.0	177
Tom Moore (A3)	20.0	370
Snake Pass	10.5	518
Regression: Rainfall total = $3.392 + (0.035 * \text{Altitude})$		
Correlation: $r = + 0.695$ % explanation = 48.3%		

in the lowlands was sporadic, except around midday when a perturbation on the cold front (identified by the London Weather Centre by a warm front symbol) caused more protracted rainfall, but of low intensity (3 mm hr⁻¹). However, in the uplands intensities rise to 6 mm hr⁻¹.

Despite winds in the range force 3 to 5, enhancement in this storm seems to have been over the highest ground, and not further east. Evidence for this comes from comparing Snake Pass and Tom Moore, as well as from the higher intensities noted at escarpment gauges such as Bottoms Reservoir and Greenfield, and at the high gauge on Holme Moss (582 m). No hyetographs were available for the lowland east. It is also notable that rainfall was much more continuous over high ground, in that the overall increase in total comes in part from "enhancement" but also partly from low-intensity rainfall which only occurs over the higher ground. Thus, comparing the 38 mm total at Snake Pass with the 13.5 mm at Stanley Reservoir, 16 mm is estimated to be added by enhancement and 8.5 mm by additional rainfall.

Overall, these three storms suggest that 'pure' orographic enhancement can provide additional hourly rainfall amounts of up to 3 mm. The rainfall is generally coincident with the high ground, but in high winds, the pattern can be displaced downwind somewhat. In all three cases described, the enhancement was associated with fronts, although more detailed evidence would be needed to distinguish between rainfall in advance of the surface front and rainfall as the surface front passes (cf Browning et al, 1975). Under such conditions, one can expect a good correlation between rainfall and altitude, though perhaps the relationship is curvilinear as Burt (1980) and Ballantyne (1983) have suggested for long-term average totals in the Pennines and West of Scotland

respectively. If convectional instability is also involved, we can expect more complex rainfall distributions spatially and temporally, however, since 'pure' enhancement without convection seems to be relatively rare (on the evidence of radar), convectional influence is most likely to be involved in any given storm. However, we must note that our sample of storms did not include many 'winter' events and may therefore be biased. Even so, it seems likely that any attempts to predict within-storm rainfall distributions in upland areas, such as the southern Pennines, will have to contend with a mixture of feeder-seeder and convective mechanisms, yielding patterns generally accordant with altitude, but with localised 'random' cells superimposed on this pattern.

5.3.3 Conclusion to Upper Derwent rainfall

Of the storms analysed, the majority display a variation in total rainfall over the catchment. In most cases, the variation exceeds $\pm 20\%$ of the arithmetic mean rainfall and displays an east-west trend over the catchment. Despite patterns of storm total distribution being repeated these cannot easily be related to the prevailing synoptic conditions. Significant correlations did however occur between storm totals and topographic variables, particularly those depicting the general form of the topography as opposed to the detail of each rain gauge site.

When storms were analysed at hourly or 15 minute periods, the storm total patterns were not maintained throughout the duration of the storm. Cells of high intensity rainfall of very limited spatial extent (in the order of $0.5 \text{ km}^2 - 2 \text{ km}^2$), developing and moving unpredictably, dominate the total rainfall distribution. These cells are most often observed in the upper reaches of the catchment but this could be purely a sampling

deficiency. Those areas hit by a raincell usually receive a large amount of rainfall which, when added to the 'background rainfall', significantly enhances the storm total. As the presence, size and location of these cells cannot be predicted they can only be incorporated into a prediction model by a random component. Alternatively, as the cells do appear to have a preference for the upper reaches of the catchment, there may be a need to have a more dense raingauge network in that area. However, it is likely that for runoff modelling purposes these cells are too limited in spatial extent to affect the size or shape of the river hydrograph at the basin outlet (see Chapter 7); it is much more important to incorporate the general pattern of the rainfall distribution at somewhat larger time periods (one hour rather than 15 minutes).

5.4.1 Relationship between southern Pennine-scale rainfall and topography

For each raingauge site, long term average annual rainfall (1950-1971; LTAAR) was correlated with several topographic features to determine the long term relationships between the two. LTAAR had a correlation of 0.651 with "spot height" but this increased to 0.803 with "maximum altitude with 2 km radius". When "maximum altitude with 5 km radius" was used the correlation dropped to 0.771. For a sample of 36 gauges, a correlation of $r = 0.418$ is significant at the 1% level; thus all three correlations are very significant. This suggests that of the three altitude measurements, LTAAR is most associated with altitude within 2 km radius. This tends to confirm the importance of the 2 km scale found with individual storms at the Upper Derwent scale. Similar results were found in the Huddersfield area (Burt, 1980). As the LTAAR consists of the superimposition of many rainfall events from many different meteorological conditions, it seems plausible that certain storm types will exist which add a major contribution to the (annual) rainfall distribution. We can hypothesise that these storm events should be dominated by altitudinal controls as has already been indicated on the Upper Derwent scale and by the factor analysis of daily rainfall patterns in Chapter 4. Table 5.8 identifies the observed events which had high

Table 5.8 Rainfall events highly correlated with LTARR

Date	Correlation	Meteorology
1.7.83	0.790	Trough, warm front
2.9.83	0.732	Vigorous depression
17.9.83	0.849	Warm front, cold fronts
8.10.83	0.731	Active fronts
2.11.83	0.849	Weak warm fronts
26.11.83	0.664	Frontal

correlations with LTAAR, and gives their associated meteorological conditions. It is interesting that all six storms involved fronts or troughs, though at least one was relatively inactive.

Table 5.9 gives correlations between storm totals and altitudinal measures. Correlations with spot height were generally low with correlations greater than 0.65 only occurring on three occasions. What was more surprising, considering the results for LTAAR, was the correlation of storm rainfall with altitude in a 2 km or 5 km radius. Although generally higher, for only 2 and 6 occasions respectively were the correlations greater than or equal to 0.65 (8 and 7 occasions respectively correlate above 0.6). Correlations with "maximum altitude within 5 km radius" were slightly higher than those with "maximum altitude within 2 km radius". This perhaps suggests that topography on the 5 km scale is more important in instigating rainfall than at 2 km or spot height scale. This contrasts with results found with LTAAR; this is likely to be a function of the cumulative nature of the variable LTAAR. Rainfall events classified as convectional (17.7.83, 23.7.83 and 31.7.83) all had low correlations with altitude. This is to be expected as convectional rain-fall is triggered by surface heating and is not particularly associated with higher ground. Further, once instigated, convectional cells tend to move in a random fashion and would not necessarily be related to any topographic features.

The raingauge catch in the Upper derwent has been shown not to be associated with gauge altitude or local topography and confirms the pattern found for the wider S. Pennine scale. If instead, "distance to Bleaklow" is substituted for gauge height, higher and significant

Table 5.9 Relationship between storm totals and (i) LTAAR, and
(ii) altitude : S. Pennine scale

Date	LTAAR	Gauge altitude	Max. altitude within	
			2 km radius of the gauge	5 km
31.5.83	-0.332	0.251	0.29	0.007
28.6.83	0.499	0.192	0.643	0.681
1.7.83	0.790	0.472	0.701	0.829
17.7.83	0.218	0.140	0.268	0.367
23.7.83	0.280	0.334	0.259	0.226
31.7.83	0.114	0.022	0.237	0.119
16.8.83	0.128	-0.068	0.206	0.172
31.8.83	0.100	-0.078	0.119	0.310
2.9.83	0.732	0.633	0.695	0.669
9.9.83	0.384	0.276	0.606	0.457
16.9.83	0.459	0.452	0.554	0.693
17.9.83	0.849	0.650	0.621	0.561
5.10.83	-0.057	-0.312	-0.573	-0.646
6.10.83	0.493	0.126	0.467	0.533
8.10.83	0.731	0.355	0.624	0.521
26.11.83	0.664	0.702	0.698	0.697
8.12.83	0.580	0.171	0.313	0.152
9.12.83	0.393	0.374	0.572	
2.11.83	0.849	0.24	0.278	
25.11.83		0.479	0.651	
14.12.83	0.308	0.171	0.340	
25.12.83	-	0.704	-	

correlations result. Table 5.10 provides examples of the correlations found between the Derwent gauge catches and altitude measurements and, as a comparison, correlations for the S. Pennine gauges between gauge catch and altitude within 2 km radius. The results again suggest that the role of topography is scale dependent. There is reasonably good correspondence between the S. Pennine scale correlations and distance to Bleaklow correlations in most cases. The largest mismatch, on the 31 August is probably a result of the local convective nature of the storm.

Table 5.10 Correlations between storm totals and altitudes

Date	Gauge altitude (Derwent gauges)	1 km radius (Derwent gauges)	Distance to Bleaklow (Derwent gauges)	2 km radius (S. Pennines)
27 May	0.027	-0.460	-0.112	-
28 June	0.112	-0.298	0.302	0.643
1 July	0.102	0.384	-0.886	0.701
31 July	-0.026	0.166	-0.035	0.237
31 Aug	0.320	0.640	-0.808	0.119
9 Sept	-0.049	-0.572	0.282	0.606
16 Sept	-0.124	0.051	-0.861	0.554
SCALE	LOCAL	REGIONAL	LOCAL	REGIONAL

Calculation of rainfall gradients for the Southern Pennine region

The rainfall gradient (mm/100 m rise) is calculated using the slope of the linear regression equation between total storm rainfall (mm) and raingauge altitude (m). When the relationship is curved the rainfall has been logarithmically transformed before calculation. The regional rainfall gradient has been calculated using all available raingauges.

Gradients have also been calculated in the same fashion but using raingauges from either west or east of the Pennine divide. The regional rainfall gradient varies from 11.7 mm per 100 m rise to 0.17 mm/100m with 85% of events being less than 5.0 mm/100 m rise (Table 5.11). The west and east slope gradients on the whole tend to be less steep, though there are maxima of 9.4 mm/100 m on the west slope and 17.0 mm/100 m on the east slope. 75% and 70% of events respectively are below 5.0 mm/100 m for the west and east slope gradients. On 60% of occasions the east slope gradient is steeper than the west slope.

The tendency for low rainfall gradients to the west of the divide indicates that often there is high, uniform rainfall in that area, increasing only a little over the Pennines on the opposite slope, the generation of rainfall will be much reduced as the air mass subsides and warms and hence the steeper rainfall gradient. This is frequently visible on the isohyet maps but can be obscured using correlation when there is a lag over the Pennine divide.

The intention was to classify storm events by rainfall gradients but too few suitable events have made this difficult to achieve. The notion behind the classification is that the process causing precipitation will have a characteristic rainfall gradient. At one extreme is the purely convective rainfall in which rainfall is generated independently of topography. Under these conditions, the rainfall gradient could be the largest possible if for example a small convective storm was triggered at the top of a catchment and covered only part of it. Equally easily, the rainfall gradient will be shallow as the cell moved from high to low ground. At the opposite pole is the pure orographic event in which the

Table 5.11 Regional rainfall gradients (mm/100 m)

Date	Regional	West	East	Difference
9.12.83	11.70	2.41	17.0	14.59
2.9.83	9.02	6.92	7.67	0.75
25.11.83	6.98	6.97	3.88	<u>3.09</u>
9.9.83	4.90	4.4	3.96	<u>0.44</u>
25.12.83	3.62	-	-	-
8.10.83	3.49	5.0	4.82	<u>0.18</u>
16.9.83	3.36	2.02	7.37	5.35
8.12.83	3.09	5.20	2.52	<u>2.68</u>
17.9.83	2.99	2.22	0.66	<u>1.56</u>
23.7.83	2.85	0.45	3.97	3.52
26.11.83	2.81	0.42	3.53	3.11
1.7.83	2.36	2.94	7.0	4.06
31.5.83	1.95	0.14	0.91	0.77
2.11.83	1.37	0.51	0.35	<u>0.16</u>
17.7.83	1.27	0.77	7.33	6.56
14.2.83	0.95	1.60	2.06	0.46
16.8.83	0.85	9.40	1.45	<u>7.95</u>
28.6.83	0.71	2.74	3.66	0.92
31.8.83	0.61	0.73	4.03	3.3
31.7.83	0.17	0.63	6.6	5.97

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TOPOGRAPHIC CONTROLS ON RAINFALL AND RUNOFF(U)
NUDDERSFIELD POLYTECHNIC (UK) DEPT OF GEOGRAPHY
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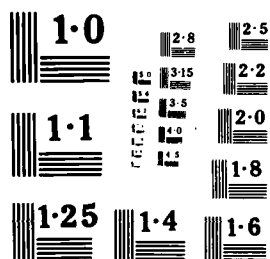
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only precipitating mechanism are the feeder-seeder clouds. Under these conditions, the maximum rainfall will be on the highest ground with a consistent decline with height. Given the ideal meteorological conditions, this event should be entirely predictable. In between these two extremes; the convective and the orographic, are an infinite number of events composed of a combination of frontal, convective and orographic processes. The rainfall gradient resulting will depend on the mix of predictable (feeder-seeder) and unpredictable processes (convection). Included in this "middle" category would be the event on 9 September 1983 (see Chapter 6) in which frontal rainfall was supplemented by the high ground triggering convective instability. This 3-stage model is summarised in Table 5.12.

Table 5.12 Framework for rainfall pattern classification

Rainfall Class	Pattern	Rainfall Gradient	Case example
Convective	Unpredictable	variable	17.7.85
Frontal	↓	↓	9.9.83
Orographic	Predictable	x mm/hr	25.12.85

Comparison of Regional and Derwent scale rainfall gradients

A limited number of rainfall gradients for both the Regional and Upper Derwent scale have been plotted to compare the enhancement with altitude. The regional rainfall is calculated independently of raingauges in the Upper Derwent catchment. With the exception of two events (31 Aug. and 6 Oct.) the Derwent rainfall gradients are considerably lower than the regional rainfall gradients (Table 5.13).

Table 5.13 Comparison of Regional and Derwent scale rainfall gradients

Date (1983)	Regional mm/100m	Derwent mm/100m
1 July	2.36	0.44
31 July	0.17	0.065
31 Aug	0.61*	0.628
9 Sept	4.9	-0.37
12 Sept	9.02	0.97
17 Sept	2.99	-1.16
6 Oct	0.47*	1.66
2 Nov	1.37	0.601

This may be a result of the size of the Derwent catchment in relation to the general influence of the hills. It is possible that rainfall processes cannot react to the shape of the Derwent within the few kilometers width of the catchment. The significance of the difference between regional and local rainfall gradients will be considered later.

On the occasion of 9 Sept, the Derwent rainfall gradient is negative in contrast to a relatively high positive regional gradient. However, when rainfall totals are plotted on the regional map it is evident that the storm centre is well to the east of the Pennine divide (see also Chapter 6). A high (calculated) rainfall gradient results but it must be noted that correlations with altitude ($r = 0.276$) and with LTAAR ($r = 0.384$) are low.

Classification of rainfall events

Attempts have been made to classify storm totals into groups by cross-correlating the storm rainfall totals at each site and by cross-

correlating descriptors of the rainfall pattern such as rainfall gradient, relationship with LTAAR, etc.

The cross correlation matrix between eighteen rainfall events produced a wide range of results. A few strong correlations exist (see Table 5.14) but, no discrete groups are obvious when links between rainfall events are drawn up. Similar analysis was done on the Upper Derwent storm totals with much stronger correlations between events.

Table 5.14 Correlation matrix of rainfall totals for southern Pennine storms

	31 May	28 Jun	1 Jul	17 Jul	23 Jul	31 Jul	16 Aug	31 Aug	2 Sep	9 Sep	16 Sep
28 June	0.242										
1 July	0.395	0.896									
17 July	0.359	0.778	0.956								
23 July	0.766	0.594	0.844	0.860							
31 July	0.227	0.787	0.937	0.990	0.777						
16 Aug	-0.134	0.573	0.254	-0.018	-0.126	0.004					
31 Aug	0.328	0.829	0.977	0.995	0.837	0.989	0.080				
2 Sept	0.759	0.680	0.722	0.548	0.769	0.452	0.448	0.579			
9 Sept	0.703	0.691	0.677	0.474	0.682	0.385	0.553	0.517	0.991		
16 Sept	0.568	0.803	0.973	0.958	0.945	0.912	0.088	0.959	0.759	0.694	
17 Sept	0.629	0.101	0.056	-0.170	0.236	-0.282	0.462	-0.136	0.725	0.763	0.117
5 Oct	0.530	0.802	0.933	0.828	0.857	0.773	0.336	0.858	0.876	0.843	0.928
6 Oct	0.099	0.952	0.927	0.827	0.588	0.848	0.525	0.880	0.612	0.612	0.815
8 Oct	0.458	0.874	0.819	0.619	0.641	0.574	0.679	0.678	0.917	0.934	0.765
26 Nov	0.786	0.501	0.784	0.824	0.993	0.736	-0.230	0.790	0.719	0.623	0.906
8 Dec	0.344	0.679	0.517	0.246	0.330	0.201	0.862	0.324	0.833	0.893	0.441
9 Dec	0.755	0.645	0.873	0.870	0.997	0.791	-0.056	0.855	0.802	0.723	0.960
2 Nov	0.579	-0.288	-0.072	-0.163	0.289	-0.285	-0.069	-0.172	0.475	0.453	0.060
25 Nov	0.531	0.443	0.407	0.150	0.404	0.063	0.633	0.209	0.915	0.958	0.402
14 Dec	0.360	0.954	0.936	0.794	0.704	0.773	0.567	0.845	0.822	0.822	0.867
31 May	1.000	0.242	0.395	0.359	0.766	0.227	-0.134	0.328	0.759	0.703	0.568

17 Sep	5 Oct	6 Oct	8 Oct	25 Nov	8 Dec	9 Dec	2 Nov	25 Nov	14 Dec
0.361									
0.003	0.647								
0.538	0.903	0.841							
0.217	0.802	0.498	0.556						
0.735	0.681	0.621	0.913	0.242					
0.259	0.889	0.637	0.694	0.982	0.390				
0.772	-0.267	-0.243	0.185	0.329	0.293	0.276			
0.886	0.685	0.412	0.845	0.349	0.933	0.450	0.722		
0.284	0.933	0.952	0.959	0.618	0.775	0.753	-0.011	0.644	
0.629	0.530	0.099	0.458	0.786	0.344	0.755	0.579	0.531	0.360

5.5.1 Calculation of basin mean rainfall

Dense autographic raingauge networks are difficult and expensive to operate in small upland catchments and yet appear to be necessary for realistic estimates of mean basin rainfall. It has already been argued that a single raingauge at the outlet of the Upper Derwent would, on almost all occasions, provide a very poor estimate of mean basin rainfall. This becomes more important as the time period over which the rainfall is reduced from annual to hourly intervals. This section compares some of the standard networks of calculating basin rainfall to the Upper Derwent network and identifies the most valuable sites within the Upper Derwent for location of a reduced number of raingauges.

5.5.2 Comparison of standard methods

Four methods of calculating mean basin rainfall have been compared using weekly rainfall totals from the Upper Derwent network. This temporal scale was chosen to compare the various methods of calculating because the data was readily available using the manual storage gauges and the same principles apply for within-storm periods. The results from the arithmetic mean and the Thiessen polygon mean are very similar but the distance weighted method always produced consistently higher estimates (Table 5.15).

Figure 5.25 THEISSEN POLYGON NETWORK

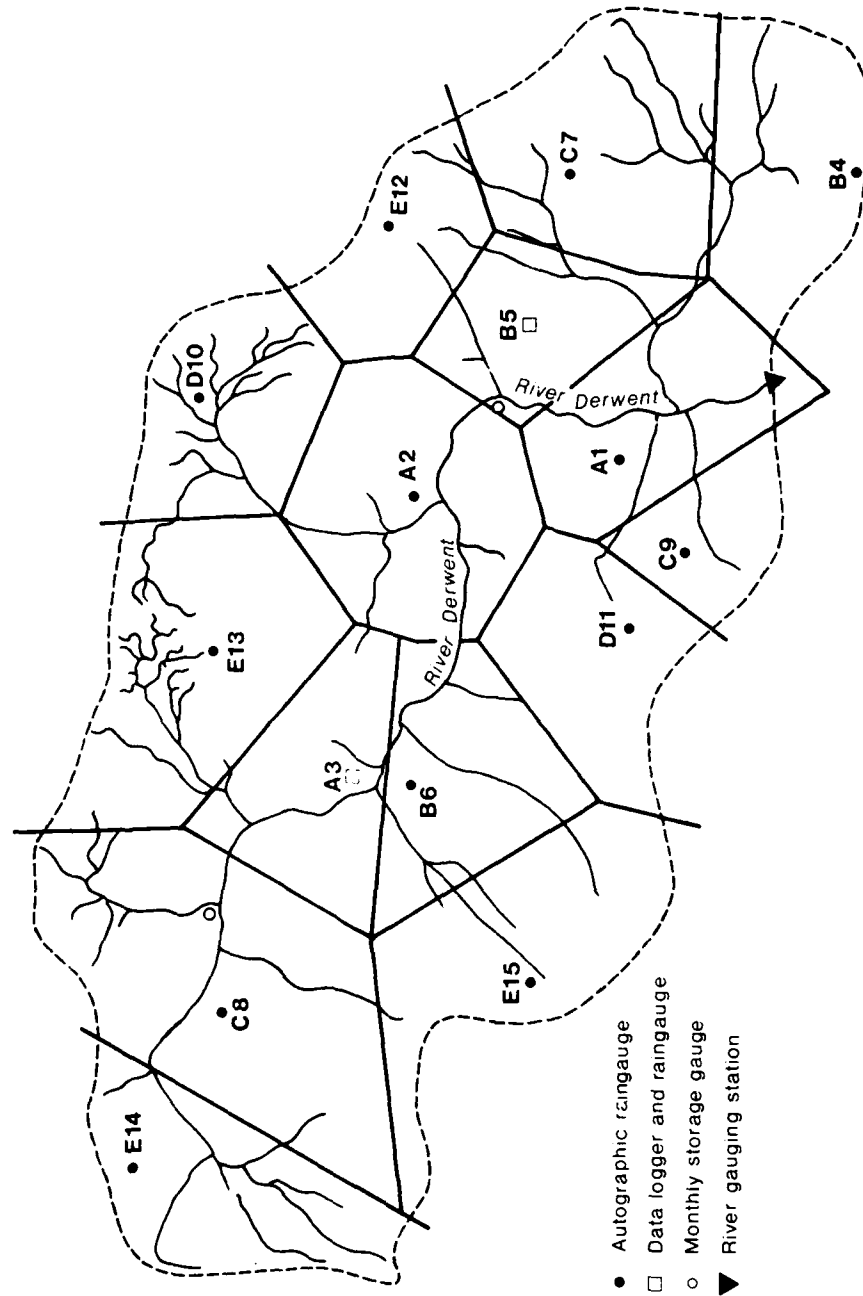


Table 5.15 Comparison of different methods of calculating mean basin rainfall

Date (week ending)	Unweighted mean (Arithmetic)	Theissen mean	Distance weighted mean*	Trend surface mean
25.5.83	46.12	46.3	44.62	45.95
6.6.83	3.48	3.48	4.04	
14.6.83	9.6	9.9	10.10	
21.6.83	3.12	2.9	3.6	
29.6.83	8.89	8.54	9.25	
6.7.83	11.5	11.69	11.75	
12.7.83	0.5	0.5	1.19	
19.7.83	3.48	3.92	4.44	
26.7.83	9.9	9.86	9.97	
1.8.83	7.56	7.53		
9.8.83	4.5	4.54		

*Program listing in Appendix A.

A close inspection of the topographic features of the Theissen polygons formed using the full raingauge network suggest that it may not be such a reliable method when the raingauges are less dense and poorly located. The method assumes that the defined areas have the same rainfall as that of each centrally located raingauge (Fig. 5.25). Taking altitude range as an example, the polygon enclosing gauge C9 has a relative relief of 315 m, ranging from 150 m to 465 m and yet, enclosing only 0.5 km². At the opposite extreme the polygon E15 enclosed 1.27 km² and has a height difference of only 20 m. Similar problems arise with slope angle and aspect (Table 5.16 summarises selected topographic parameters for the complete network). This would suggest that for the Upper Derwent

Table 5.16 Topographic characteristics of each polygon in the full raingauge network

	Area (Km)	Altitude range (m)	Maximum altitude (m)	Minimum altitude	Dominant aspect
A1	1.09	160	420	260	129
A2	1.44	211	521	310	227
A3	0.94	85	440	355	220
B4	1.09	100	440	340	296
B5	0.78	185	485	300	245
B6	1.04	170	520	350	45
C7	1.45	236	546	310	243
C8	2.15	190	590	400	25/185
C9	0.5	315	465	150	78
D10	0.94	98	488	390	235
D11	0.94	150	495	345	52
E12	0.7	56	541	485	210
E13	1.55	117	527	410	217
E14	1.13	120	590	470	40
E15	1.27	20	555	535	45

All measurements taken from 1:10000 OS map.

altitude-weighted polygons may be more appropriate. For the Upper Derwent an improvement may also be made if an east-west trend were incorporated into the area of influence around the raingauges. The third method considered, the distance-weighted mean produces consistently higher estimates of basin rainfall. As the actual basin rainfall is not (and cannot) be calculated, no method can be said to be "correct". However, because of the close similarity between the arithmetic and Thiessen polygon means, the former has been taken as a base in the following analysis. This method has the added advantage over the

Theissen Polygons that no extra calculations have to be made every time a failed gauge changes the network.

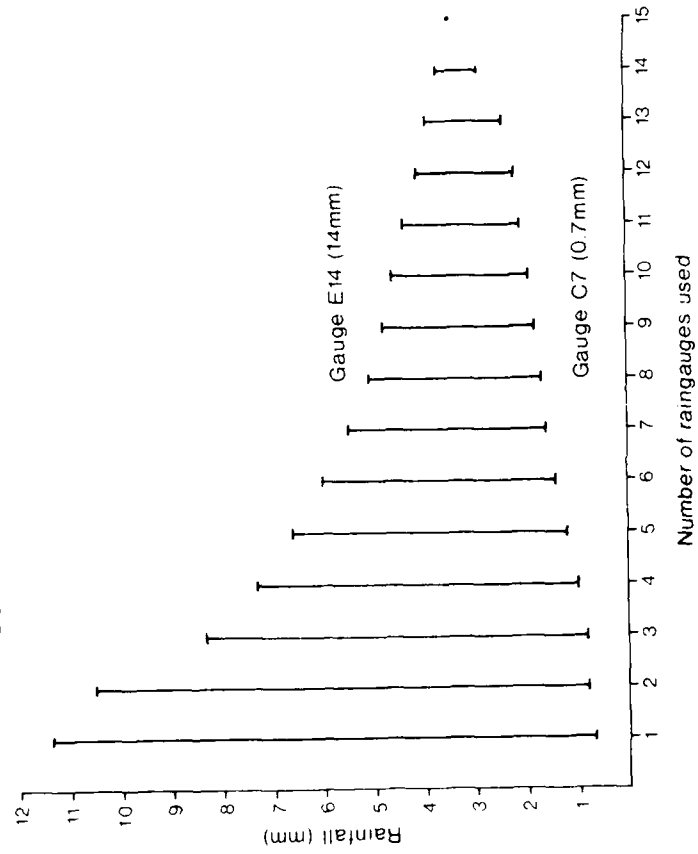
5.5.3 Prediction of the rainfall distribution from a less dense network

Mathematical methods of calculation have already been reviewed in Chapter 1 and compared in Chapter 5.5.2 assuming a fixed number of rain-gauges. It is apparent that even with a rain-gauge network as dense as that of the Upper Derwent, quite significant differences in totals can be obtained by different computational methods. A further problem needing consideration is that of predicting the rainfall distribution from less dense rain-gauge networks. This study offers an ideal opportunity of estimating:

- a) the importance of individual gauges within a dense rain-gauge network;
- b) identifying optimum locations of the rain-gauges in the reduced network;
- c) the optimum number of rain-gauges necessary for adequately calculating mean basin rainfall.
- d) methods of predicting the pattern of rainfall around the single gauge.

Points a) and b) would suggest that some locations within a catchment may be more influential than other areas for estimating mean basin rainfall. The extent to which this is true it is suggested is dependent on the type of rainfall occurring. Frontal rainfall for example is generally characterised by a more uniform rainfall pattern than non-frontal convective events. Convective rainfall would theoretically be best measured by a very dense grid pattern rain-gauge network in contrast

Figure 5.26 RELATIONSHIP BETWEEN BEST AND WORST ESTIMATES
OF MEAN BASIN RAINFALL (arithmetic mean) 17.7.83
CONVECTIVE STORM



to the sparse linear configuration required for a pure orographic event. Thus the configuration and density of raingauge networks would, ideally be dependent on rainfall type as illustrated in Table 5.17.

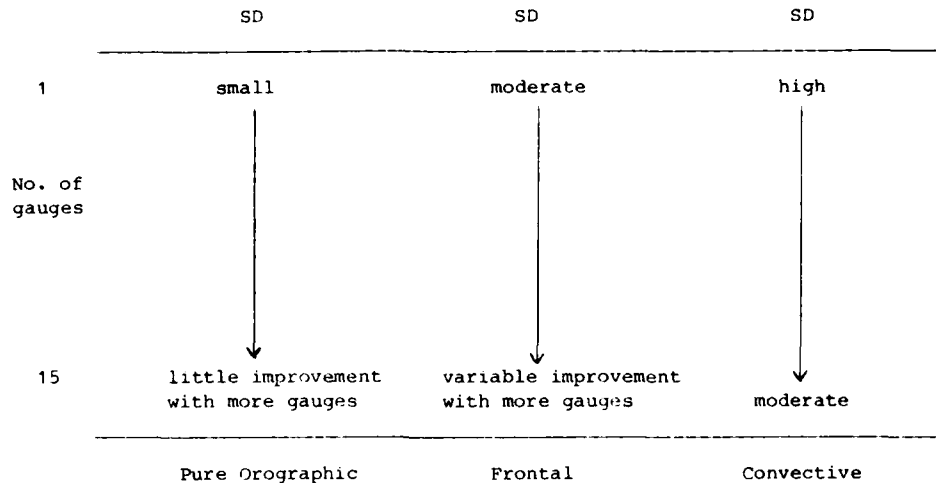
Table 5.17 Influence of storm type on the raingauge network

Storm Type	Raingauge Density	Configuration
convective	very dense	grid pattern
frontal	↓	↓
orographic	sparse	linear with altitude

In addition to the location of raingauges, the number of gauges is also fundamental to the accurate estimation of rainfall totals. Figure 5.26 illustrates the degree to which the estimation can vary using anything between one and fifteen raingauges. The best estimate of mean basin rainfall (using here the arithmetic mean) is 3.5 mm using all fifteen gauges. As the density of raingauges decreases, the range in answers increases irrattically so at the most extreme, mean basin rainfall with a single raingauge could be calculated as 0.7 mm or 11.4 mm or, almost anything in between. This case is based on a convective storm (17.7.83) which reached only the upper portion of the catchment and is thus theoretically probably the most extreme. It does tend to illustrate, however, that convective storms can be very poorly estimated. Although not tested, it is anticipated that this type of analysis can be applied to other storm types to illustrate the importance of storm type on rainfall estimation with convective storms at one extreme and pure orographic events at the opposite. Thus, standard deviations of

estimates for each storm type may eventually be able to be stated (Fig. 5.27).

Figure 5.27 Influence of synoptic type on the required number of rain-gauges for a given accuracy of basin mean rainfall



Given that within the Upper Derwent catchment the rainfall distribution cannot be easily predicted from synoptic conditions or topography without reference to the wider southern Pennine area, what is the minimum rain-gauge network that will provide adequate rainfall data for runoff modelling? It has already been shown that for convective rainfall a single gauge is inadequate. However, if only a single rain-gauge was available which site would provide the most information? To ascertain this, for all events, the arithmetic basin mean rainfall was regressed against individual gauge totals. A regression line slope of unity and the lowest standard error should therefore be the most representative. Table 5.18 provides the resultant regression equations. Gauge A2 appears to be the most representative site for a single gauge to judge basin mean rainfall, the scattergram is displayed in Figure 5.28.

Figure 5.28 SCATTERGRAM OF A2 GAUGE TOTALS
AND BASIN MEAN TOTALS

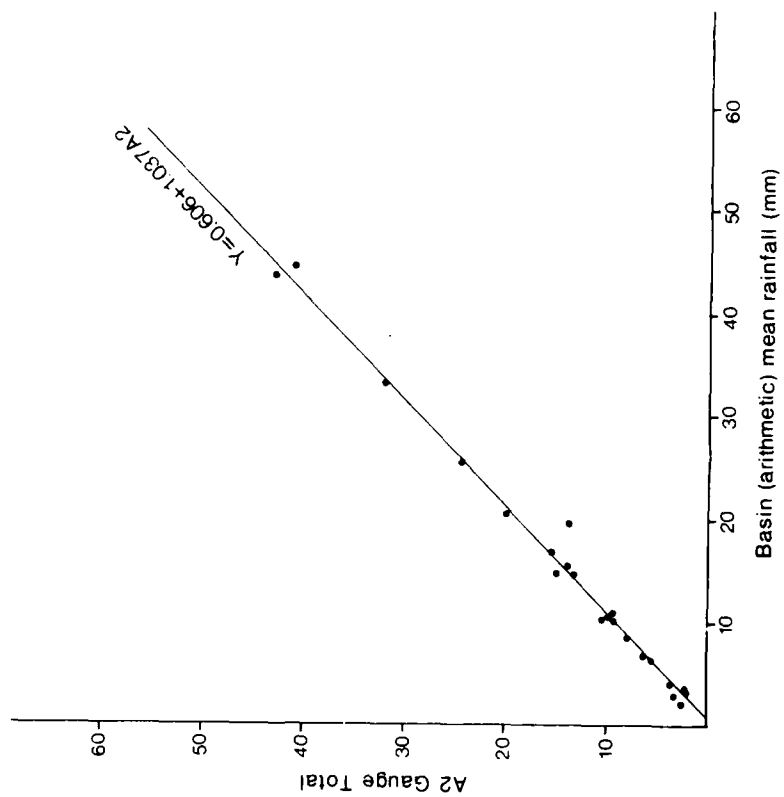


Table S.18 Regression of basin mean (arithmetic) on gauge total

$$Y = a + bx + \text{error}$$

Site

A1	$Y = 1.445 + (0.823 \times A1)$
A2	$Y = 0.606 + 1.037 \times A2$ SE = 0.026 98.8%
B4	$Y = 0.0508 + 1.156 \times B4$
B5	$Y = 0.741 + 1.145 \times B5$
B6	$Y = 1.072 + 0.854 \times B6$
C7	$Y = 2.498 + 0.793 \times C7$
C8	$Y = 0.146 + 0.867 \times C8$
C9	$Y = 0.806 + 0.815 \times C9$
D10	$Y = -0.143 + 1.156 \times D10$
D11	$Y = 0.533 + 0.977 \times D11$ SE = 0.027 98.6%
E12	$Y = 2.706 + 0.767 \times E12$
E13	$Y = 0.592 + 0.886 \times E13$
E14	$Y = -1.428 + 1.068 \times E14$
E15	$Y = -0.5 + 0.946 \times E15$

Although gauge D11 had a lower intercept and a slope closer to unity, raingauge A2 explained a greater percentage of the variance (D11 explained 98.6% and A2 explained 98.8%). Given also the more accesible nature of site A2 this would be the more practical location.

If a greater number of raingauges were available, more detailed spatial data and therefore a more accurate value for basin mean rainfall could be achieved using three raingauges. These would be best sited in a NW-SE line through the catchment to take account of the most frequent trend in rainfall as discussed in section 5.2.2. This then would enable convection events confined to only part of the catchment to be measured.

To conclude, if only a single raingauge was available for monitoring rainfall over the Upper Derwent catchment, a gauge at site A2 would produce the most representative data.

5.6 Conclusion

The observed variation between identically installed raingauges at different locations could be attributed to two causes. Firstly, to a real variation in rainfall receipt and secondly, to random error. This random error can be a result of the variability of rainfall on a very small scale as a result of, for example, the distribution of water droplets in precipitation. To identify the presence and magnitude of this and thereby eliminate it from 'real' variation a microne트워크 of five Snowdon manual raingauges were installed at a randomly selected site (A2). All gauges were within 30 cm of each other and installed at ground level by gravel as all other gauges in the network. The variation between the gauges was much less on all occasions than the variation observed over the entire catchment (Table 5.19). Thus, the spatial variation in rainfall receipt observed over the Upper Derwent catchment is a real variation and not random error. It has been shown that within the Upper Derwent, because of the limited size of the catchment and the presence of raincells in many events recorded, the rainfall distribution cannot easily be predicted. A good idea of the degree of variation over the catchment can be obtained from three raingauges or alternatively with raingauges in conjunction with radar. This is further expanded on in Chapter 6. It should be noted however, that given the size of the Upper Derwent catchment the observed variation in rainfall receipt does not have a discernible influence on the river hydrographs. To conclude, the most important influences on the distribution of rainfall within the Upper Derwent appear to be firstly the location of the catchment in relation to the topography of the southern Pennines; the catchment is too small to greatly influence any rainmaking processes. Secondly, the presence and character of high intensity localised raincells moving within the catchment.

Table 5.19 Microscale variation in rainfall receipt compared to the wider network

Date	Basin mean (mm)	Maximum basin (mm)	Nearest gauge catch (A2) (mm)	Range in four gauges (mm)	Variation as % of catch	Basin variation as % of basin mean
26.7.83	9.86	3.1	9.4	0.1	1.06	31.4
1.8.83	4.54	4.8	6.6	0.4	6.06	105.7
9.8.83	4.5	2.1	4.0	0.4	10.0	46.7

Chapter 6 An Evaluation of Rainfall Radar in the Southern Pennines:

A case study from 3 - 10 September 1983

6.1 Introduction

Although not originally one of the aims of the research project, it soon became apparent that the rainfall data collected could be compared to available rainfall radar estimates. Radar data was made available by the UK Meteorological Office Rainfall Radar Laboratory at Malvern. The field area falls within the Hameldon Hill radar (NGR 3809 4287) which is located about 50 km north-west of the Upper Derwent, well within the acceptable range of rainfall radar systems (75 km). Given the large number of continuously recording raingauges available (both of our own and also the Water Authority gauges), this provided the opportunity for an extensive comparison with the local radar system, comparable to those reported by Harrold et al. (1973) and by Hill et al. (1981). Given the time needed to analyse a series of radar scans by hand (the original digital data was not available), we were limited to the analysis of one case study, the storm of 9-10 September 1983, which has been mentioned in the previous chapter. Thus the analysis reported here represents a wide spatial coverage, but is necessarily confined to a single synoptic situation. As already noted, the use of rainfall radar has great potential with respect to distributed rainfall-runoff modelling, since it offers complete spatial coverage of the basin in real time. The calibration of the radar is clearly crucial and can lead to large errors in the predicted rainfall total, particularly if few or no calibrating raingauges are available.

The use of radar to detect rainfall has been extensively described in the literature, and it is not our purpose to review those accounts here (see for example, Harrold (1966); Harrold et al. (1973); Huebner (1984). However, some points deserve emphasis. The main problem of using rainfall radar systems lies in calibrating the radar echoes: pulses of electromagnetic radiation are emitted in very rapid succession and are intercepted in the atmosphere by particles over 200 micron diameter. The radar beam is reflected by these particles, the strength of echoes received back at the radar being related to the intensity of precipitation occurring. The echo pattern is converted by the computer into plan position and displayed on a VDU as a matrix of grid squares or pixels. Use of the 'radar equation' (Probert-Jones, 1962) relates the radar character and the echo strength to the intensity. The echo power is proportional to the number and diameter of the droplets present in the atmosphere ($\epsilon n D^6$) which in turn is related to the rainfall intensity (I):

$$\epsilon n D^6 = c I^d$$

Unfortunately the 'constants' c and d are not constant but vary from 80 to 660 and from 1.2 to 1.9 respectively (Probert-Jones, 1962; Battan, 1973). One technique to overcome this problem is to use independent measurements from telemetering raingauges to calibrate the radar. The radar:rainfall ratio varies over time with the type of rainfall and empirical calibrations are selected depending on the rain-fall type (Collier, 1985). For the radar scans analysed here, most were classified as 'frontal', although 'rain shadow' and 'showers' were also included. Collier (1985) has reported seasonal variations in radar accuracy with a tendency for radar overestimation in winter (due to bright bands ie. an

effect produced during melting of cloud particles) and underestimation in summer. He also noted a fluctuation in radar accuracy during the passage of cyclonic systems, though this can be reduced by using calibration procedures. Clearly the use of a calibrating raingauge helps reduce the errors involved, particularly if more than one calibration site is used (This demands the use of tele-metry for real-time calibration, of course). Since the character of cloud systems may vary over space, especially in upland terrain, some error in the radar prediction is to be expected. For the Dee Weather Project in North Wales, errors between -15% and +20% have been reported for three hour totals within 20 km of the calibrating gauge (Harrold et al., 1973).

Further difficulties are encountered over upland areas. In order to avoid ground reflection ('clutter') the radar beam must be aimed at a higher angle. This means that over more distant areas the beam may be at some considerable height and may be unable to detect important low-level droplet growth processes, such as those associated with feeder-seeder mechanisms. For this reason, the radar may underestimate rainfall intensities in upland areas, as noted by Hill et al. (1981) for example. The problem of clutter is not entirely avoided even when the radar is located on top of a hill, as with the Hameldon Hill gauge. It is interesting to note that Collier concluded that the use of radar for operational flood forecasting is cost-effective (compared to operating a dense network of raingauges) but that for the North West Radar Project, there was still the need for further telemetering rain-gauges for real-time calibration of the 15-minute scans. This implies a continuing problem of radar calibration in upland areas and suggests that radar inaccuracy is likely for this case study also.

6.2 A brief description of the radar data

Figure 6.1 shows a typical hard-copy for the Hameldon Hill radar. The coastline of north-west England has been added and the study area is also shown. Perusal of the radar scans showed that analysis of a 40 x 40 km area centred on the Upper Derwent would provide adequate spatial coverage without taking too long to decode each map. To have included a wider area would have increased the analysis time considerably. With hindsight, extension to the east towards Sheffield would have led to the inclusion of a storm cell associated with the occlusion (see Section 6.3); the western edge of this cell is only just included on the maps analysed. To have covered the area further west over Manchester would not have added much to the analysis since the only rainfall in that area was related to the stationary occlusion and did not include an orographic component. It should be noted that the Upper Derwent area is not calibrated using telemetering raingauges; the only calibration involves the radar equation and a subjective assessment of rainfall type.

The hard copy on figure 6.1 shows a matrix of type symbols, each representing a 2 x 2 km grid square. Thus the radar analysis deals with a matrix of 400 pixels in a 20 x 20 square. It is clear from figure 6.1 that the entire Upper Derwent is covered by only 7 pixels! Each scan gives the estimated hourly intensity for each pixel : although the result of an instantaneous scan, each plot was assumed to represent the rainfall intensities prevailing during the 15-minute period which ends with the scan time. The total rainfall during each scan period is therefore one quarter of the hourly intensity value mapped. Though a shorter period between radar scans might seem preferable, at least for calibration

purposes, it would achieve very little since it would be difficult to disaggregate the raingauge records to much less than quarter-hour divisions. Thus the 15 minute gap between radar scans, whilst giving some element of inaccuracy especially during high-intensity rain, is still quite acceptable for most purposes.

Records from the data-logger and autographic gauges showed that the complete 'rainfall day' of 9 September (0900 9.9.83 to 0900 10.9.83) would be covered by analysing the period from 2017 GMT 9.9.83 to 0802 GMT 10.9.83. By taking the complete period of rainfall during the 'day', this meant that the manual raingauges in the local area could also be used in any spatial comparison of gauge and radar totals. Thus 12 hours of radar scans were decoded, 48 maps in all. The hard copy provided by the Meteorological Office used the 43 Level Display Scheme given on table 6.1. It was decided to record a value of zero for those pixels where rain was recorded by the radar, but where the intensity was below 0.25 mm per hour (symbol "). We were less interested in the presence or absence of rain than in the intensities recorded; intensities below 0.25 mm per hour are too low to be accurately gauged by the Casella pen-chart system, and it might take several hours before a tipping bucket gauge was activated. In any case such low intensities are probably of little importance hydrologically. This convention certainly saved some time during the decoding, but it does mean that the data provided may very slightly underestimate rainfall (but only by a few tenths of a millimetre) and more seriously, our maps will underestimate the area affected by 'rain'. Over a period of 12 hours this could introduce some errors in rainfall totals (up to 3 mm only), but not for individual 15-minute maps.

Each of the 48 radar scans was decoded and stored as a separate data file on disk on an Apple microcomputer. Subsequent analysis of these files included the summation of hourly rainfall totals, correlation between rainfall totals and grid-square altitude, the production of summary statistics for each file, and mapping of the rainfall distributions. In addition, comparison between radar estimates and rain-gauge total was also accomplished via regression analysis using the Apple. Figure 6.2 maps the relief of the study region (elevations in hundreds of metres). The three major upland peaks of Kinder Scout, Bleaklow and Holme Moss show up clearly; the Upper Derwent is immediately to the east of Bleaklow.

Fig 6.1 : An example of a radar scan "hard copy" for the Hameldon Hill radar, with the study area marked.

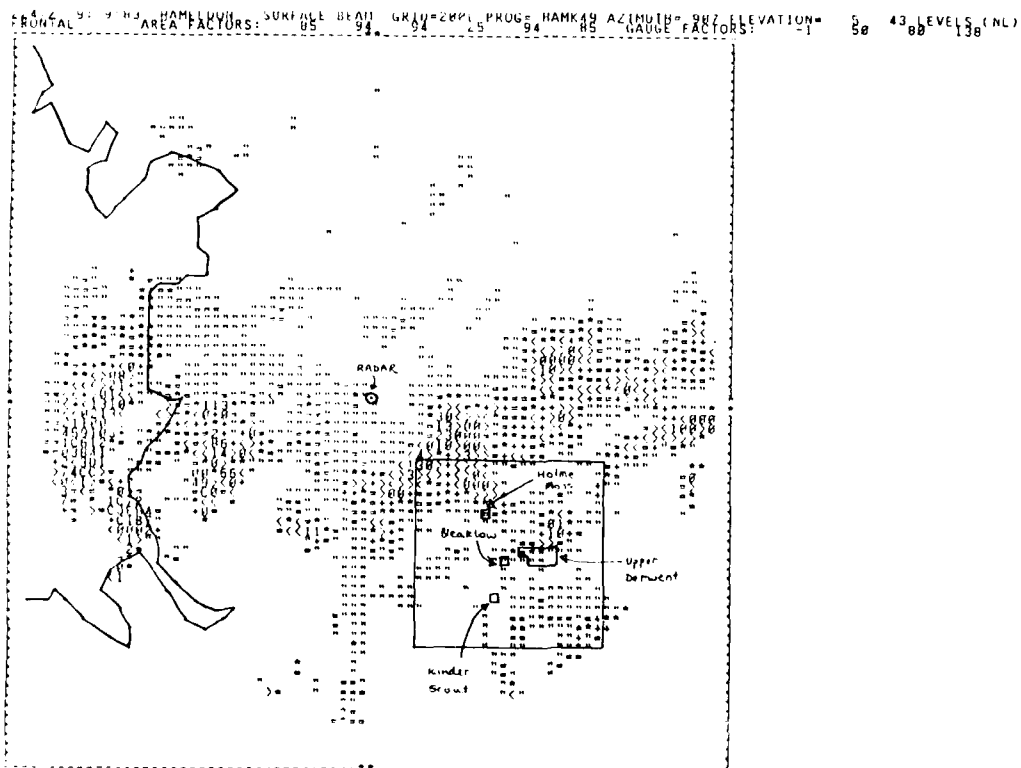
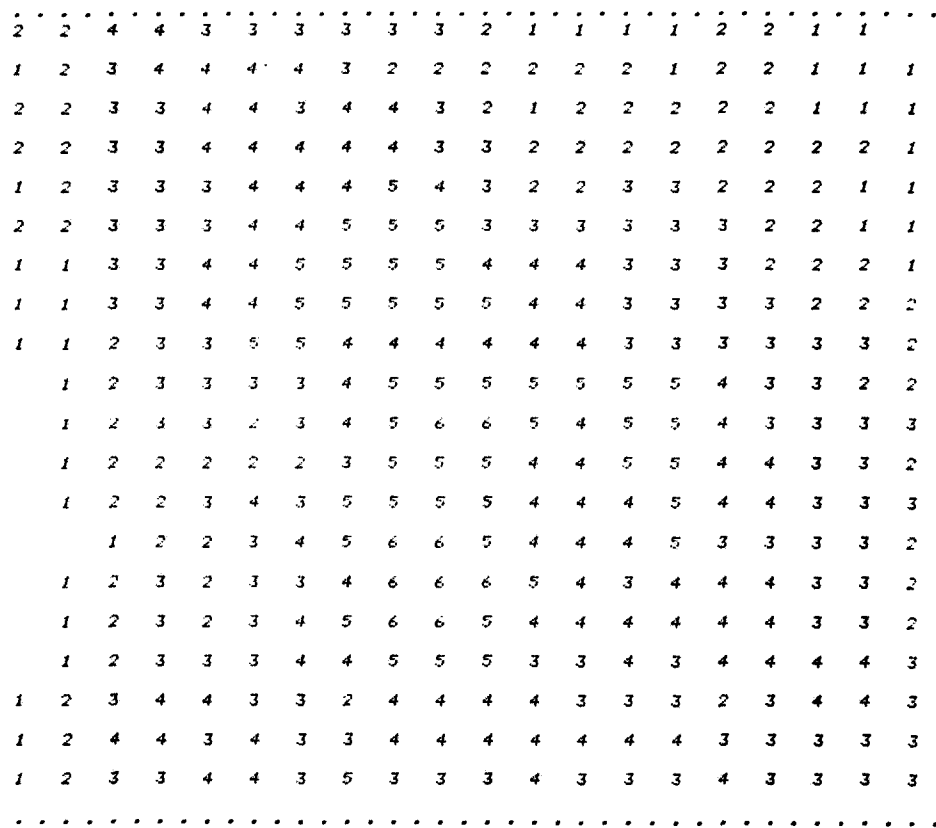


Table 6.1 The 43 Level Display Scheme used to decode the radar scans.

RANGE	SYMBOL	RANGE	SYMBOL	RANGE	SYMBOL
0.0	blank	2.5	1	8.0	C
0.0+	"	3.0	2	10.0	D
0.25	=	3.5	3	12.0	E
0.5	*	4.0	4	14.0	F
0.75	+	4.5	5	16.0	G
1.0	<	5.0	6	18.0	H
1.38	>	5.5	7	20.0	I
1.88	0	6.0	8	22.0	J
		6.5	9	24.0	K
		7.0	A	26.0	L
		7.5	B	28.0	M
				30.0	N
				32.0	O
				40.0	P
				48.0	Q

All values in millimetres per hour. 'Range' comprises that between the value given and the next highest value tabulated. The scale continues to code Z (120 mm); the highest valued decoded here was code O.

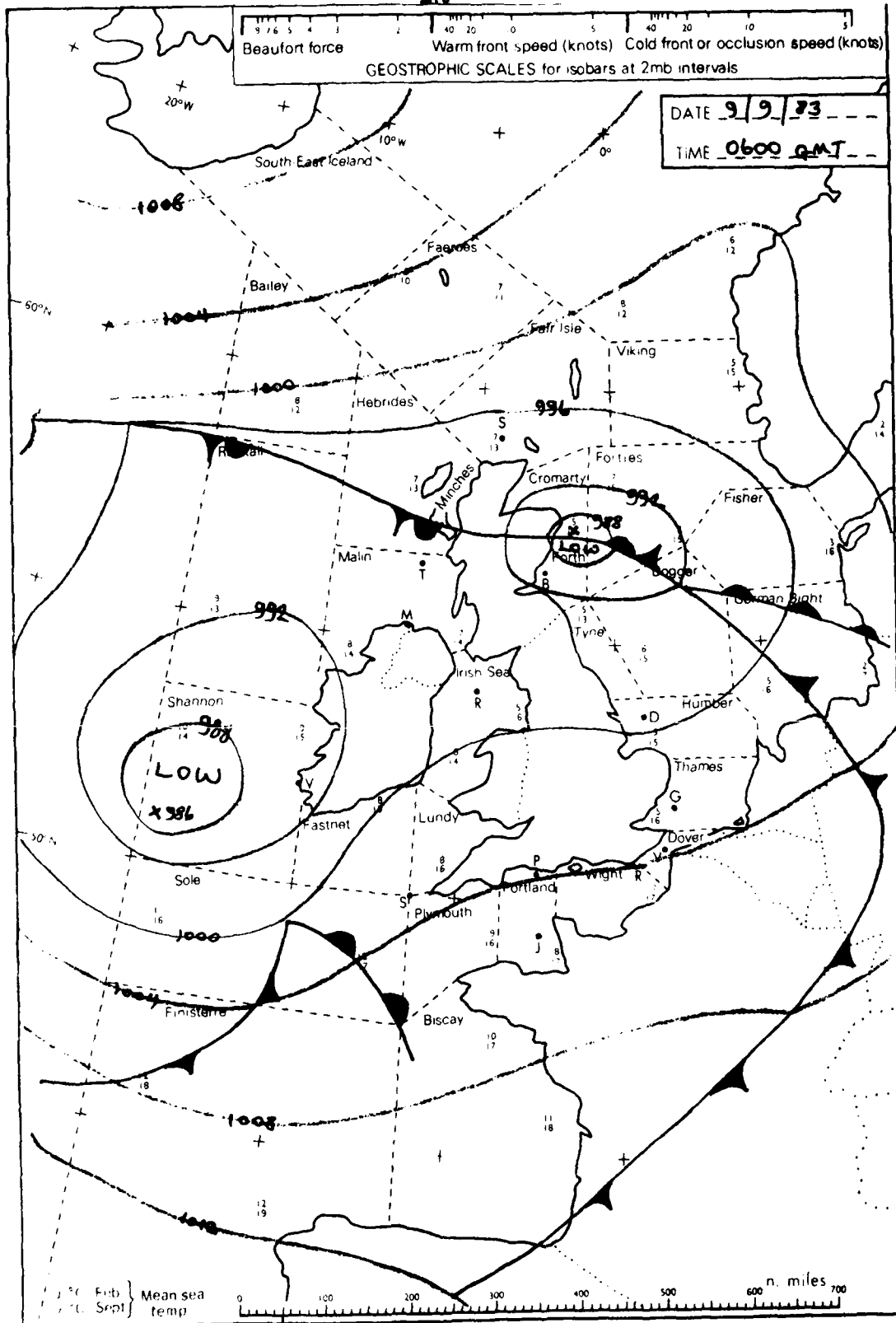
Fig 6.2 : Relief map of the southern Pennines (elevations in hundreds of metres).



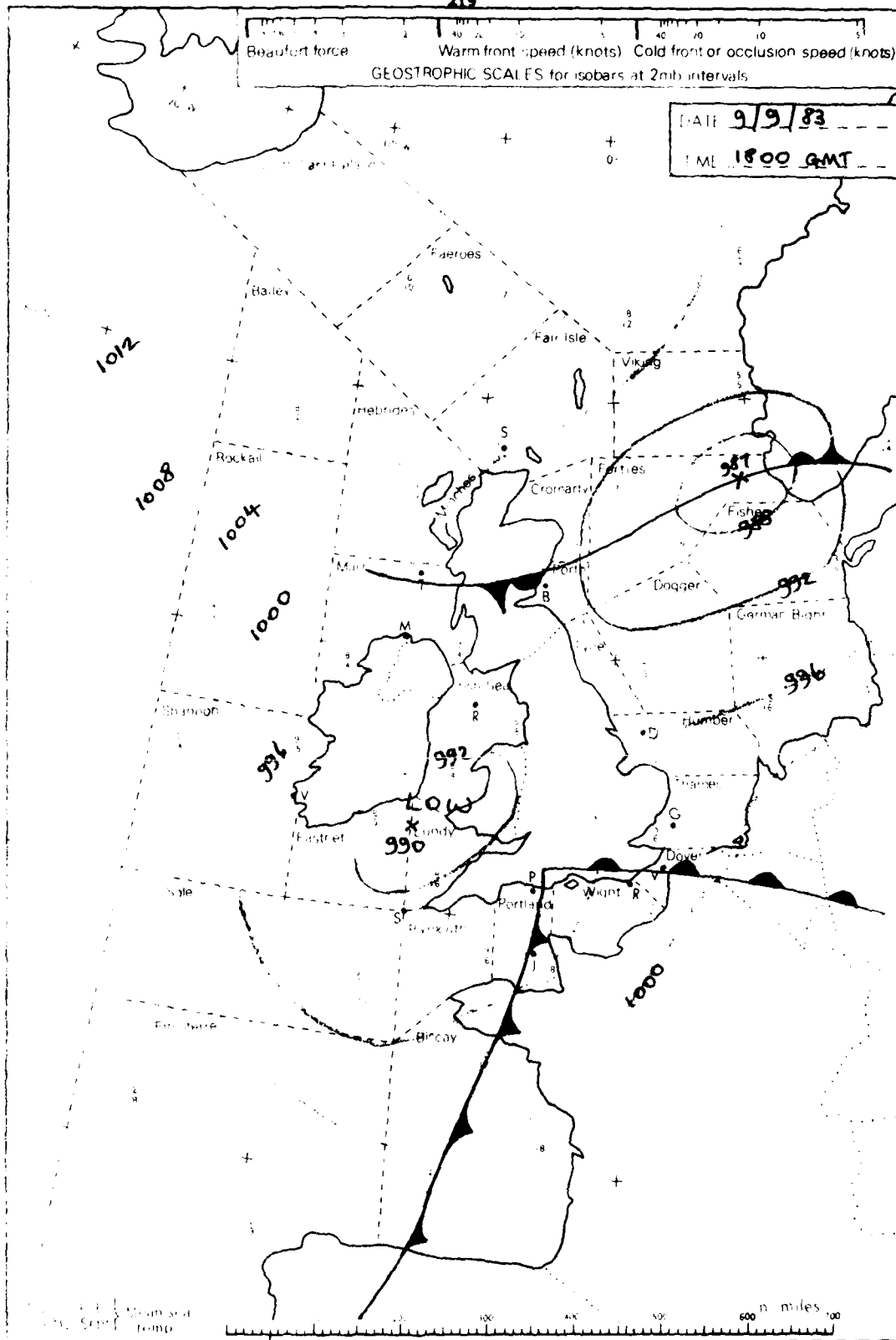
6.3 A brief description of the synoptic situation for the event
9-10 September 1983

Figures 6.3 and 6.4 summarise the developing synoptic situation during the case study event. The surface chart for 0600 GMT on the 9th shows a Low of 986 mb south-west off Ireland which is creating a strong north-easterly flow over England and Wales. An occluded front lies over Scotland with its associated Low in Sea Area Cromarty. The upper air chart confirms this north-easterly flow (figure 6.4) and it is no surprise that a classic cyclonic frontal system begins to develop in the Bay of Biscay, given the general situation. By 1800 on the 9th, the depression system has matured and moved over the South Coast with the Low filling slightly to 990 mb and moving east. By 2400 on the 9th the fronts have occluded and reached the southern boundary of the Pennines. Thereafter the occlusion moves only a little to the north, where it stagnates, rotates somewhat anticlockwise, and finally moves into the North Sea by 1800 on the 10th., having deepened again to 984 mb. Whilst this meteorological information remains at a rather general level, it suggests that the rainfall received in the southern Pennines after 2000 was all associated with the occlusion, although it is possible that the warm and cold fronts were still separate entities, given the two periods of rain which occurred (see below). The Daily Weather Summary, issued by the London Weather Centre, reported that rain spread to most places in England late on the 9th and that the 10th was 'a dull wet day' in northern England: 'Rain was persistent and often heavy especially in North Wales, the South Pennines and East Yorkshire'. Winds were light and variable, given the stagnant occlusion, and were not perhaps ideal for engendering low-level feeder clouds (up to 1 km altitude - generated by low-level uplift over the hills) over the northern hills therefore (Browning et al., 1975).

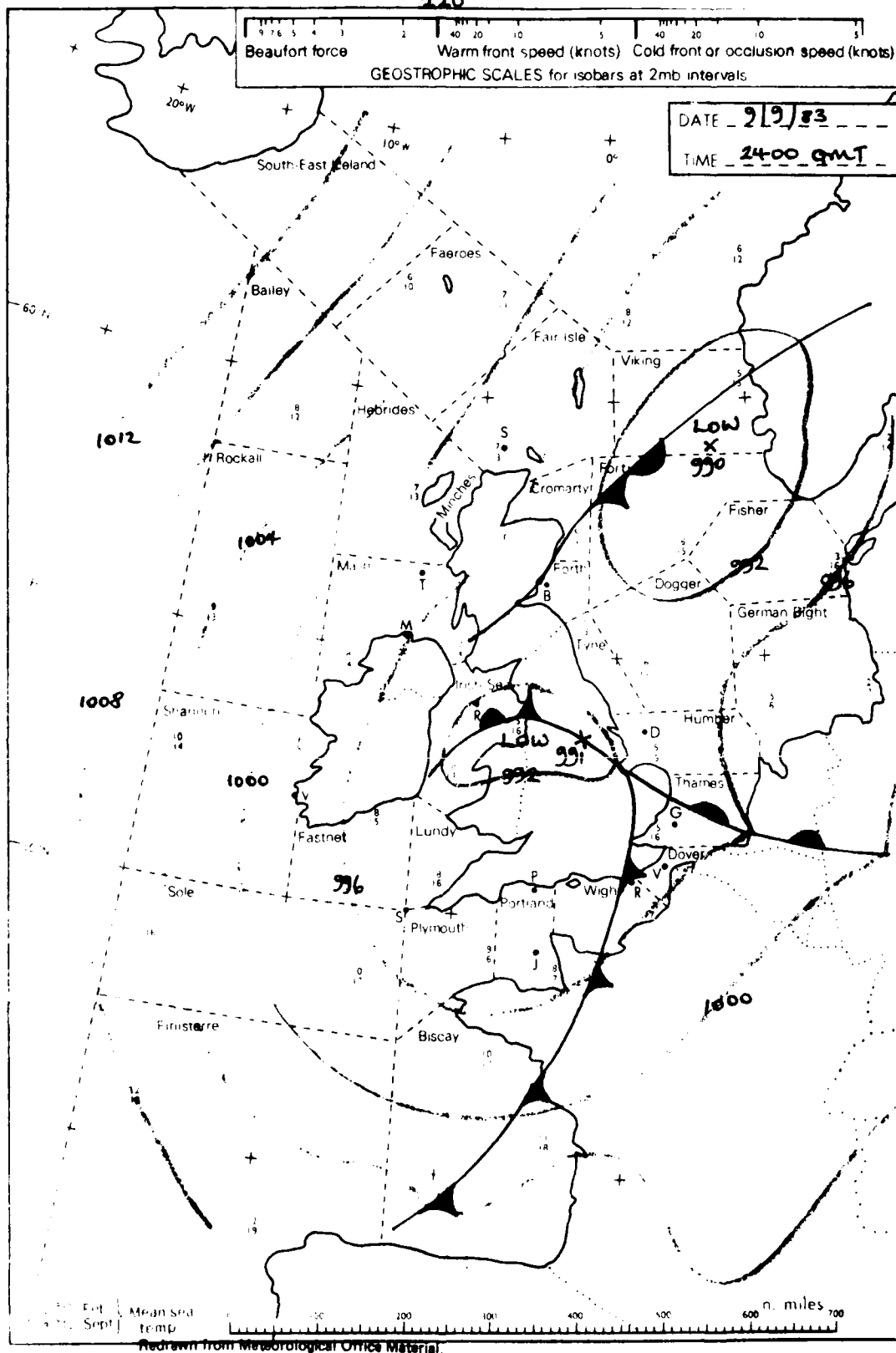
Fig 6.3 : Surface synoptic meteorology for the period of the storm event of 9th/10th September 1983.

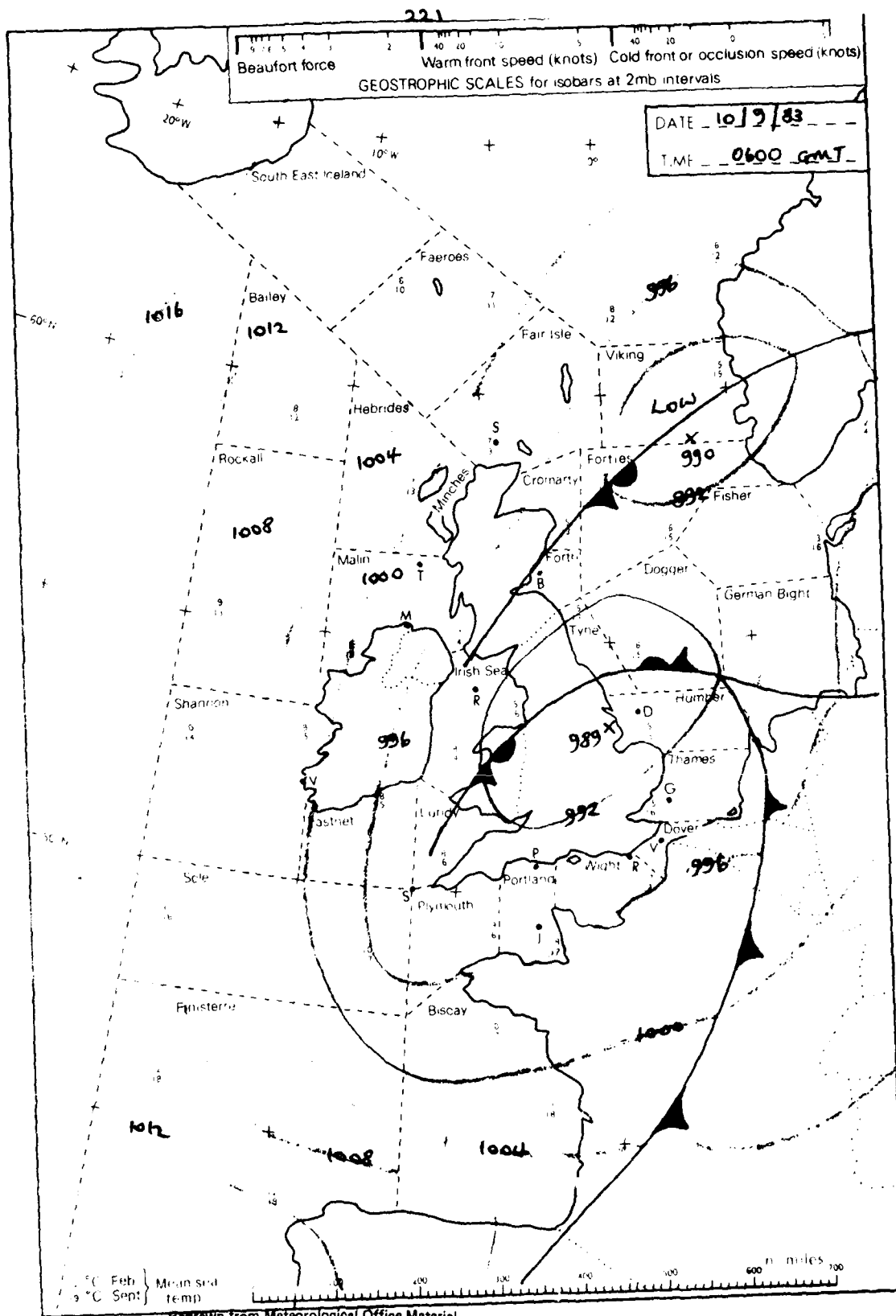


Redrawn from Meteorological Office Material.



Redrawn from Meteorological Office Material.





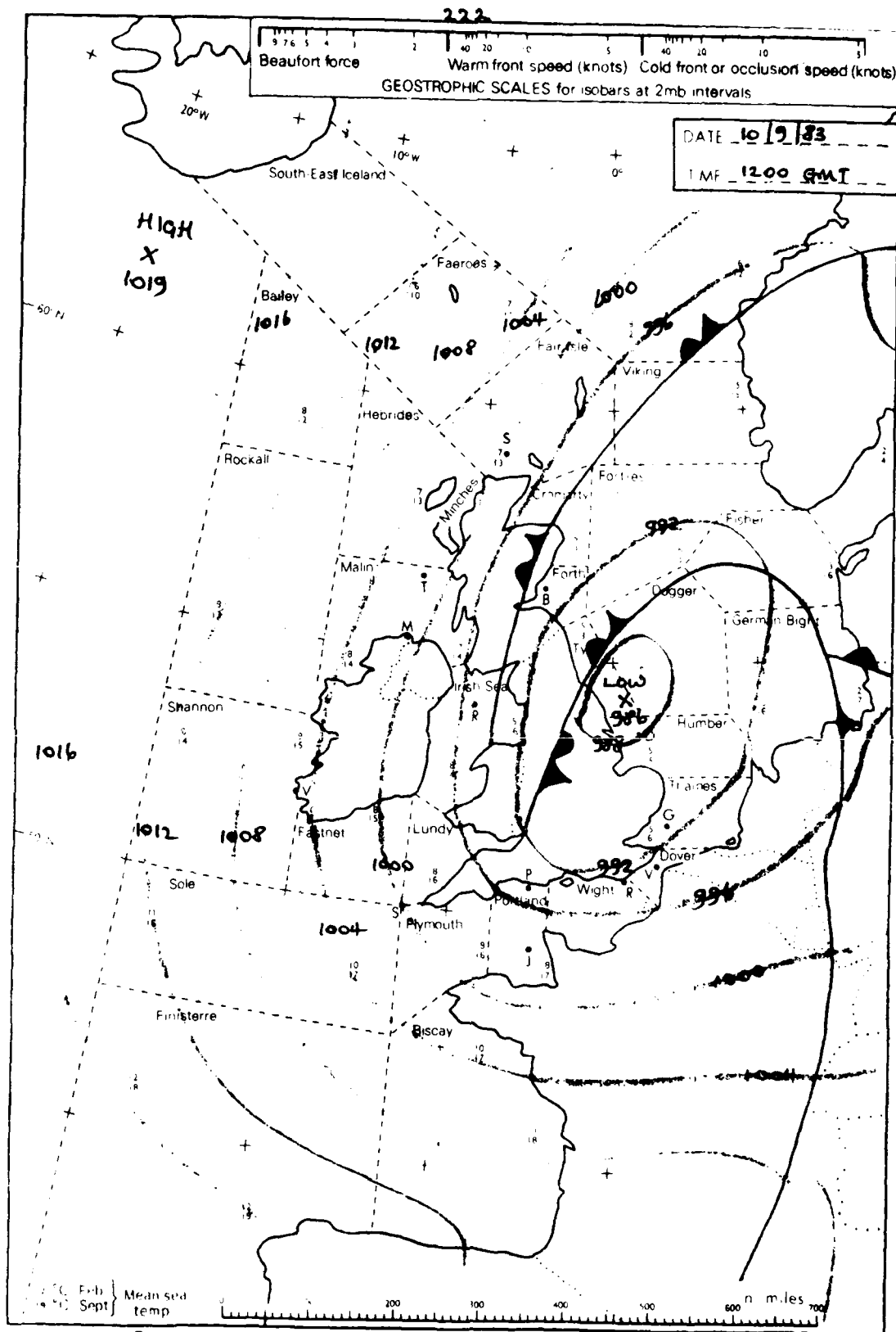
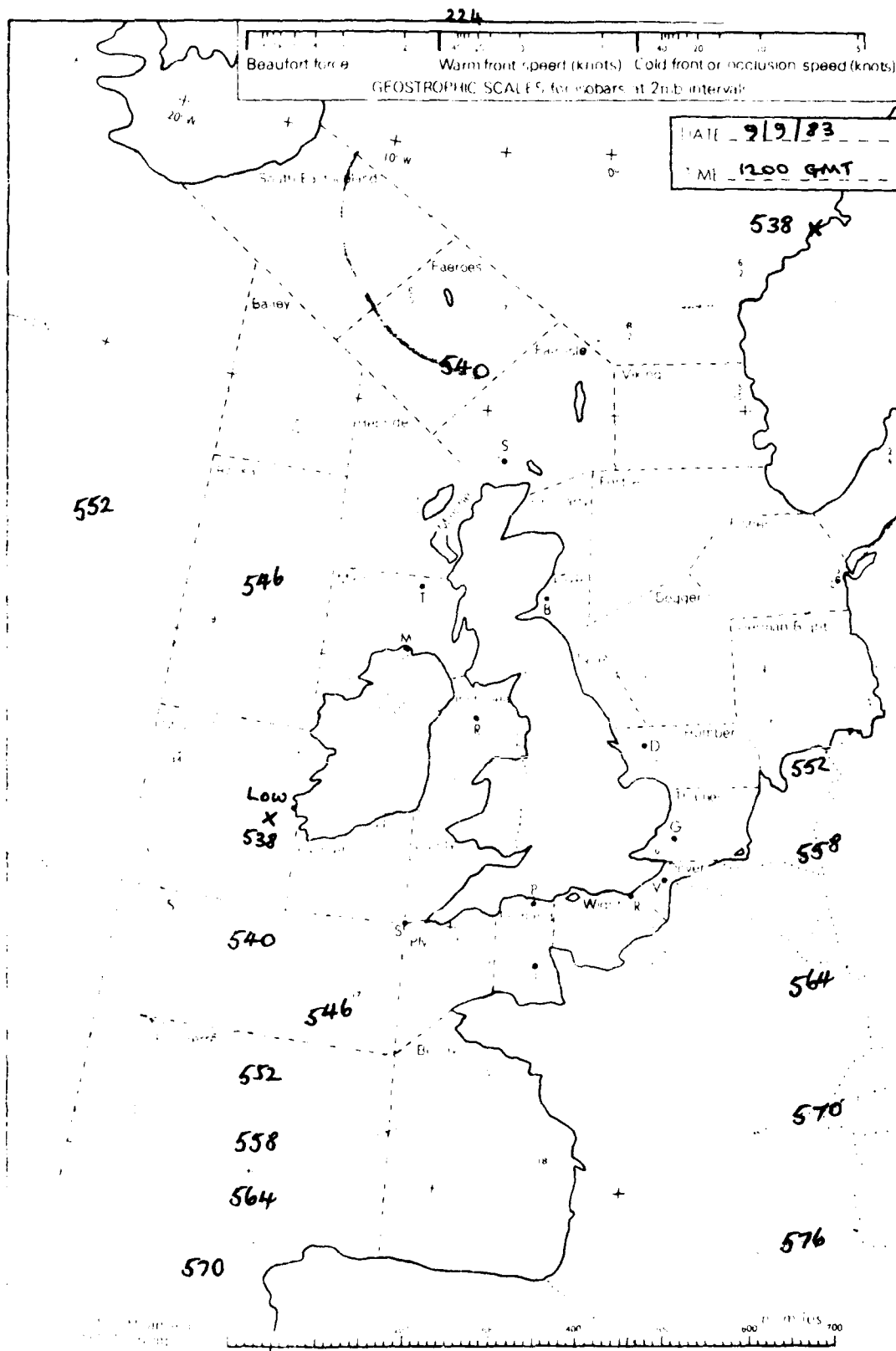


Fig 6.4 : Upper air chart for 9th September 1983 (1200 GMT).



Redrawn from Meteorological Office material.

500 mb surface elevation.

Fig 6.5 Hourly rainfall totals (radar estimates) for the storm of 9th/10th September 1983. The FILENAME denotes the DAY and time - end of each hour - for each total.


```

1.....
0 1 0 0 0 1 0 1 1 2 0 0 0 0 0 0 0 0 0 0
0 0 1 0 1 1 1 1 2 2 0 0 0 0 0 0 0 0 0 0
0 0 1 0 1 1 1 2 2 1 0 0 0 0 0 0 0 0 0 0
0 0 0 1 1 2 2 1 1 1 0 0 0 0 0 0 0 0 0 0
0 0 0 1 2 2 2 3 1 0 0 0 0 0 0 0 0 0 0 0
0 0 1 1 1 3 3 2 2 0 0 0 0 0 0 0 0 0 0 0
0 0 1 2 1 2 5 3 1 2 0 0 0 0 0 0 0 0 0 0
0 1 1 2 2 3 4 3 1 1 0 0 0 0 0 0 0 0 0 0
1 1 1 3 4 4 5 3 1 0 0 0 0 0 0 0 0 0 0 0
0 1 1 3 3 3 4 3 2 1 1 0 0 0 0 0 0 0 0 0
0 0 1 2 3 3 3 4 2 2 1 0 0 0 0 1 0 1 0 0
0 0 0 1 2 3 3 5 3 1 1 0 0 0 1 1 0 1 1 0
0 0 0 1 1 3 4 4 5 2 0 0 0 0 0 2 1 1 0 0
0 0 0 0 1 1 2 6 9 4 0 0 0 0 0 2 1 0 0 0
0 0 0 0 0 1 2 5 7 6 0 0 0 0 0 1 1 0 0 0
0 0 0 0 0 0 0 3 6 3 0 0 0 0 0 1 1 0 0 0
0 0 0 0 0 0 0 1 4 4 0 0 0 1 1 1 0 0 0 0
0 0 0 0 0 0 0 1 2 2 0 0 0 1 2 2 1 0 1 0
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0 0 0 0 0 0 0 0 0 0 0 0 1 2 1 1 0 0 0
.....

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FILENAME : TEN01

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1 2 2 1 3 3 1 2 1 1 1 1 1 0 0 0 0 0 0 0
1 1 1 2 2 3 4 2 3 2 1 1 0 0 0 0 0 0 0 0
1 1 2 2 2 2 4 5 3 4 2 1 0 0 0 0 0 0 0 0
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0 0 1 2 4 3 4 3 5 3 2 1 1 0 1 1 1 2 3 0
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0 0 0 1 1 2 2 4 2 2 2 2 2 3 5 4 3 2 2 1
0 0 0 0 0 1 3 3 1 1 1 2 2 2 4 5 4 4 3 2
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0 0 0 0 0 0 0 0 0 0 0 1 1 1 2 4 7 5 4 1
0 0 0 0 0 0 0 0 0 0 0 1 0 1 2 5 4 6 3 1
0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 3 2 3 3 3
0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 2 2 2 3
0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 1 1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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FILENAME : TEN02

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4 3 3 3 2 1 2 2 1 0 1 1 3 2 1 1 0 0 0
2 5 5 4 4 3 3 2 2 0 0 2 3 2 3 2 1 0 0
1 1 3 4 6 4 4 3 3 3 1 1 3 3 3 2 2 1 0
1 1 3 4 4 4 3 3 3 4 3 3 3 3 3 3 4 3 1
1 1 2 5 3 3 3 3 2 3 3 4 3 2 3 4 5 4 2
0 1 1 1 2 2 2 3 2 1 2 2 2 4 5 4 5 4 3
0 0 1 2 1 1 1 2 2 2 1 1 3 5 6 6 5 5 5
0 0 0 0 0 0 0 1 1 2 1 1 2 6 8 8 5 4 5
0 0 0 0 0 0 0 0 0 1 1 1 1 3 5 6 6 5 4
0 0 0 0 0 0 0 0 0 1 1 1 1 2 3 4 5 6 4
0 0 0 0 0 0 0 0 0 0 0 1 1 1 2 3 5 4 4
0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 3 3 3 3
0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 2 2 2
0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 2 2 2
0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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FILENAME : TEN03

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3 3 3 2 3 2 3 3 2 2 2 2 3 2 2 1 1 1
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3 3 6 5 5 3 3 4 5 5 3 4 5 6 4 5 5 3
3 3 4 7 5 4 4 5 5 7 5 5 4 4 5 6 6 5
0 1 1 3 3 2 3 3 5 7 7 5 4 4 5 5 6 7
0 0 0 0 1 1 1 2 4 5 4 4 6 4 3 2 4 5
0 0 0 0 0 0 0 0 1 2 3 2 3 4 3 1 2 3
0 0 0 0 0 0 0 0 0 1 1 1 3 3 2 2 2 3
0 0 0 0 0 0 0 0 0 0 0 1 3 2 2 2 3 3
0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 2 2
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FILENAME : TEN04


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0 0 0 0 0 0 0 0 X 0 1 1 2 1 1 2 2 3 3 5 8
0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 3 4 6 8
0 0 0 0 0 0 0 0 0 1 1 1 2 2 1 2 2 4 4 5 8
0 0 0 0 0 0 0 0 0 1 2 1 1 2 1 1 2 3 3 5 7
0 0 0 0 0 0 0 0 0 1 1 2 1 1 2 2 2 3 3 4 6
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0 0 0 0 2 0 0 0 0 2 2 1 1 2 3 4 4 4 4 6 6
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0 0 1 1 1 0 0 0 2 2 2 2 3 2 2 3 3 4 6 9 X
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0 0 1 1 1 0 1 1 3 4 2 1 1 1 0 0 0 1 3 6
1 0 0 1 2 1 1 1 3 4 2 2 1 0 0 0 0 0 1 4
0 0 1 1 1 1 1 2 2 3 2 2 1 0 0 0 0 0 0 1
0 0 0 1 2 3 2 2 3 4 3 2 1 0 0 0 0 0 0 0
0 0 0 1 3 3 2 2 3 3 1 1 0 0 0 0 0 0 0 0
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0 0 0 1 8 6 4 6 3 2 1 0 0 0 0 0 0 0 0 0
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FILENAME : TEN07

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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 2
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 2 3 5
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 6 X
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 4 8 X
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 4 7 X
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 5 8
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0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 2 3 5 6 4 4 5 4
0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 2 4 5 5 3 3 3 4
0 0 0 0 0 0 0 0 0 0 0 0 0 1 2 1 3 3 3 2 2 3 3
0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 2 1 1 3 2
0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 1 1 0 1 2 0
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FILENAME : TEN08

Table 6.2 Hourly rainfall radar estimates: regression between altitude (in metres) and hourly rainfall total (millimetres). n=400

Hour ending	Intercept	Exponent	Correlation coefficient	Mean (mm)
2100	-0.974	6.7E-04	0.255	0.166
2200	0.449	5.7E-04	0.157	0.654
2300	0.467	-4E-04	-0.143	0.323
2400	0.066	2.8E-04	0.131	0.167
0100	-0.774	5.23E-03	0.471	1.101
0200	-0.093	4.45E-03	0.368	1.502
0300	1.552	2.8E-04	0.020	1.653
0400	2.788	-2.83E-03	-0.172	1.774
0500	4.358	-6.27E-03	-0.283	2.110
0600	4.540	-4.77E-03	-0.185	2.830
0700	2.343	-9.3E-04	-0.058	2.010
0800	2.243	-2.44E-03	-0.132	1.368
Stormtotal	17.853	-6.11E-03	-0.071	15.663

6.4 Rainfall radar estimates for the period 2017-0802, 9/10 September 1983

The maps on figure 6.5 (a-k) plot hourly radar rainfall estimates (integer values of totals) for the storm. It can be seen immediately that the rain fell at two separate times: a small amount falling in the hour ending 2200 GMT with the main fall commencing in the hour ending 0100 GMT and continuing through to 0800. The main band of rain moved gradually north between midnight and 0300, presumably as the occlusion drifted northwards. The belt of rain then stagnated over the northern part of the study region before drifting south-east and dissipating. Further west at this time a band of rain lay over central Lancashire; this also moved south later on but did not reach the southern Pennines. Thus from about 0247 onwards the main movement of the air masses seems to have stopped: the pattern of rain after this time is relatively stationary and is most likely related to the immobile occlusion as depicted on figure 6.3. It seems possible that the rain in the hour ending 2200 may have been associated with the warm front of the depression system, although there is no firm evidence for this. The rain early on the 10th might then have been associated with the cold front as it moved slowly north. This interpretation would mean that the occlusion occurred somewhat later than was indicated on the available surface charts (figure 6.3).

Table 6.2 provides details of linear regression analyses between altitude and the hourly rainfall totals as estimated by the radar. Similar analyses for daily rainfall total have proved useful (eg. Bleasdale and Chan, 1962; Burt, 1980). There is a significant positive relationship between altitude and rainfall during the first half of the event ie. during the time when the storm system was moving slowly towards the

03:18:45	0.50	9.14
03:21:33	0.50	10.67
03:23:54	0.50	12.80
03:27:39	0.50	8.00
03:30:56	0.50	9.14
03:36:05	0.50	5.82
03:41:15	0.50	5.82
03:48:16	0.50	4.27
03:52:58	0.50	6.40
03:55:46	0.50	10.67
03:59:03	0.50	9.14
04:03:45	0.50	6.40
04:05:05	0.50	12.80
04:10:18	0.50	7.11
04:15:00	0.50	6.40
04:21:05	0.50	4.92
04:26:15	0.50	5.82
04:30:28	0.50	7.11
04:37:30	0.50	4.27
04:47:20	0.50	3.05
04:56:43	0.50	3.20
05:07:01	0.50	2.91
05:13:07	0.50	4.92
05:20:09	0.50	4.27
05:24:50	0.50	6.40
05:32:48	0.50	3.76
05:39:22	0.50	4.57
05:46:24	0.50	4.27
05:52:58	0.50	4.57
06:03:45	0.50	2.78
06:12:11	0.50	3.56
06:24:22	0.50	2.46
06:30:56	0.50	4.57
06:40:18	0.50	3.20
06:52:01	0.50	2.56
07:21:05	0.50	1.03
07:37:30	0.50	1.83

Total for Rainfall Day 9-9-83: 36.50 mm

Table 6.6 Hourly gauge totals and radar estimates for Snake Pass

Hour ending	Radar	Gauge	Gauge:Radar ratio
2100	0.35	0	-
2200	1.69	1.5	0.89
2300	0	1.0	-
2400	0.31	1.0	3.22
0100	1.32	3.5	2.65
0200	1.22	7.0	5.74
0300	0.31	4.5	14.51
0400	0.69	2.0	2.90
0500	0	0	-
0600	1.44	2.0	1.39
0700	2.00	4.5	2.25
0800	0.50	1.0	2.00

$$\text{Gauge} = 1.025 + 1.597 * \text{Radar}$$

$$r = 0.514$$

Table 6.7 Hourly gauge totals and radar estimates for Little Moor

Hour ending	Radar	Gauge	Gauge:Radar ratio
2100	0.13	0	-
2200	0.75	0.5	0.67
2300	0.25	2.0	8.00
2400	0	0	-
0100	0.31	1.0	3.23
0200	2.10	2.0	0.95
0300	2.03	9.0	4.43
0400	1.88	3.0	1.60
0500	0.44	2.0	4.55
0600	1.84	3.5	1.90
0700	3.63	2.5	0.69
0800	0.44	1.0	2.27

$$\text{Gauge} = 0.912 + 1.127 * \text{Radar}$$

$$r = 0.524$$

Table 6.8 Hourly gauge totals and radar estimates for Flouch Inn

Hour ending	Radar	Gauge	Gauge:Radar ratio
2100	0	0	-
2200	0.60	0.5	0.83
2300	0.31	2.5	8.06
2400	0.31	0.5	1.61
0100	0.19	2.0	10.53
0200	0.59	1.5	2.54
0300	5.13	7.5	1.46
0400	4.12	9.0	2.18
0500	1.25	5.0	4.00
0600	2.57	4.0	1.56
0700	3.35	3.0	0.89
0800	0.31	1.0	3.23

$$\text{Gauge} = 0.87 + 1.391 * \text{Radar}$$

$$r = 0.86$$

Table 6.9 Linear regression and correlation between hourly rainfall totals (derived from autographic raingauges) and radar estimates.

Gauge	Intercept	Exponent	Correlation
Derwent A1	1.676	1.297	0.568
Derwent E12	1.135	1.946	0.481
Derwent E14	0.960	1.297	0.627
Derwent A2	1.796	0.835	0.371
Derwent C8	0.900	1.823	0.745
Derwent E15	1.267	1.362	0.651
Derwent C7	-0.122	3.579	0.942 (n = 8 hrs)
Derwent D11	1.432	1.378	0.666
Derwent B6	1.068	1.437	0.515
Derwent E13	1.162	1.531	0.548
Arnfield	0.633	1.097	0.803
Kinder Reservoir	0.217	1.942	0.834 (n = 8 hrs)
Greenfield	1.778	1.040	0.569

12 hours data except where stated. Gauge total is dependent variable.

Correlation significant at 0.05 level if $r > 0.476$

Correlation significant at 0.01 level if $r > 0.634$

Table 6.10 Radar and gauge intensities for the Flouch Inn data logger

Time	Radar	Gauge	G : R	Time	Radar	Gauge	G : R
2202	1.38	0.76	0.55	0302	5.50	9.14	1.66
2217	0.50	2.46	4.92	0317	6.00	9.14	1.52
2232	0	1.14	-	0332	4.00	5.82	1.46
2247	0.75	1.14	1.52	0347	4.00	4.27	1.07
2302	0	0	-	0402	2.50	6.40	2.56
2317	0	0	-	0417	1.88	4.92	2.62
2332	0	0	-	0432	1.34	4.27	3.19
2347	0	0	-	0447	0.75	3.05	4.07
0002	0	0	-	0502	1.00	2.91	2.91
0017	0	0.84	-	0517	1.88	4.27	2.27
0032	0	1.12	-	0532	1.88	3.76	2.00
0047	0.25	3.37	13.48	0547	3.00	4.57	1.52
0102	0.50	1.08	2.16	0602	3.50	2.78	0.79
0117	0.25	1.08	4.32	0617	1.88	2.46	1.31
0132	0.25	1.16	4.64	0632	7.50	4.57	0.61
0147	0	3.20	-	0647	3.00	2.56	0.85
0202	1.88	3.37	1.79	0702	1.00	1.03	1.03
0217	6.00	4.27	0.71	0717	0.75	1.03	1.37
0232	4.50	8.00	3.44	0732	0.25	1.83	7.32
0247	4.50	12.8	2.84	0747	0.25	1.83	7.32
				0802	0	0	-

6.5 Comparison of radar estimates and gauge records

Three sources of raingauge record were available: data logger output (the most reliable for timing of rainfall but only in intervals of 0.5 mm); charts from Casella autographic gauges (good for measuring intensities but a little less reliable for times of rainfall); and manual gauges (giving only rainfall day totals). Given the general accuracy of the data loggers it was decided to concentrate initially on these records. As previously noted, three loggers were located in a transect: Snake Pass (NGR 4092 3934) on the western escarpment edge; Little Moor (NGR 4174 3956) in the Upper Derwent basin and Flouch Inn (NGR 4184 4011) on the eastern dipslope. Tables 6.3, 6.4 and 6.5 reproduce the raw output from the logger 'reader' for the rainfall day 9 September 1983.

Tables 6.6, 6.7 and 6.8 give radar estimates and measured hour totals of rainfall. In addition, the gauge:radar ratio is calculated for each hour. The linear regression equations for each gauge are quite similar and suggest that there are two components to the radar underestimates: the intercept value (0.87 - 1.03) shows a general underestimation of intensities whilst the exponents (1.13 - 1.60) imply that the radar is less accurate at higher intensities. In particular, the radar does not detect the high intensities recorded in the period 0100 to 0400; this is when gauge:radar ratios tend to be highest. The radar does rather better at Flouch Inn than at the other two sites, this being reflected in the correlation coefficient; on the whole, the radar is rather more accurate towards the end of the storm when the occlusion was stationary and Flouch Inn received rather more rainfall at this later stage. Taken together, these observations perhaps suggest that the radar is most

severely underestimating rainfall intensities during the period of storm movement over the Southern Pennines: it may be that low-level feeder clouds were produced, which enhanced the rainfall over and above the convective instability already noted (and detected by the radar - table 6.2). If this interpretation is correct, then the radar has identified certain elements of the orographic rainfall from the 9-9-83 event, but has failed to detect low level processes, as perhaps would be expected given the need to use a higher radar beam angle over hilly regions. On the other hand, the radar does seem to detect the rainfall generated by the occlusion, perhaps because this involves higher clouds.

Hourly rainfall totals from the autographic gauges were also compared to the radar estimates for the 2 km grid square within which they are located. The linear regression details are given on table 6.9. The results are very similar to those already described for the data logger gauges. Except for the two gauges which failed during the storm, the intercept values all lie between 0.6 and 1.8 while the exponents are all above 1.0 except at Derwent A2. All the correlations are significant at the 0.05 level, except for Derwent A2, and for 8 gauges they are significant at the 0.01 level. All these comparisons suggest that the radar has underestimated rainfall intensities over the southern Pennines during the 9-9-83 event, especially during the period when, ironically, the best correlations between radar estimates and altitude were established. In no case did the radar detect the high intensities associated with the northern movement of the two rain 'cells'; typically the radar underestimated intensities in the hours ending 0200 or 0300 by 3 to 6 mm. At Derwent E12 the gauge recorded 14.8 mm more rain than the radar estimate.

estimates arise only when such effects are absent, or high bright band effect compensate (by chance).

It is interesting to note that the radar apparently fails to detect rainfall on 4 scans: it may indeed have not been raining at those exact times and given the 0.5 mm tipping bucket we cannot be sure. We can be more confident that short bursts of rain are sometimes missed between scans: for example, One tip of 0.5 mm occurred at 22:53:26 (table 6.5) but was in between scans and was not detected at either 2247 or 2302 when 0.75 and 0 mm/hr were estimated by the radar. One check on the radar 'stability' was provided by comparing the hourly rainfall totals estimated using all four 15-minute scans with hourly totals based on only the first and last scan in the hour. This was done for two separate hours and in both cases the totals produced were almost identical: for the hour ending 0500, the radar estimated 1.24 mm for the Flouch Inn compared to the 1.44 mm estimated from just 2 scans: respective totals for other grid squares were 0.71 and 0.92 at Black Hill, 0.63 and 0.75 at Greenfield, and 0.56 against 0.5 for one of the Upper Derwent grid squares. Thus, despite the 'instantaneous' nature of the radar scan, the radar seems to detect the general pattern of rain quite well, and can yield quite satisfactory totals even when less than four scans are available in any one hour. Clearly, if low-level enhancement processes could be detected too, the radar would do even better in upland areas. Real-time gauge calibration in this area would go a long way to solving this problem.

Finally, we can briefly consider the wider pattern of rainfall in the southern Pennines for the rainfall day 9-9-83, including total from manual as well as automatic raingauges. Using the totals for 33 gauges, as given on table 6.11, the following linear regression resulted:

$$\text{Gauge total} = 20.921 + 0.77 * \text{Radar estimate}$$

$$r = 0.838 \quad r^2 = 0.702 \quad n = 27$$

As expected, the radar underestimates total rainfall, often by 15 to 20 mm. Gauge:radar ratios are usually less than 3 even so. The radar estimates are closer in the east of the study area where the stationary occlusion provided the highest totals, probably from the clouds of reasonable altitude. At Stocksbridge the radar estimate is 44 mm whilst the actual catch is not much larger at 52.3 mm; at More Hall reservoir near Sheffield the radar predicted 45 mm, very close to the actual catch of 49.9 mm. The underestimation is worse over the upland area, as already noted: at Snake Pass the radar estimates 9.8 mm compared to a catch of 28 mm; at Digley the totals are 30 and 45 mm; and at Derwent E14, 11 and 26.7 mm. The regression equation itself confirms the radar underestimation, although the exponent shows that the highest totals are better predicted.

Table 6.11 Radar estimates and gauge totals for the 9-8-83 rainfall day

Gauge name	Gauge total	Radar total	G : R
Arnfield	23.6	9.9	2.36
Woodhead	31.5	15	2.10
Hayfield	16.5	5	3.00
Greenfield	37.8	17.1	2.21
Blackmoorfoot	38.3	23	1.66
Bobus	45.7	25	1.83
Digley	45.5	24	1.90
Holmestyes	46.5	25	1.86
Huddersfield Oakes	33.1	21	1.58
Emley Moor	37.9	16	2.37
Stocksbridge	52.3	44	1.19
Bradfield Filters	36.4	21	1.73
Ingbirchworth	36.4	21	1.73
Langsett	39.0	30	1.30
More Hall	49.9	45	1.11
Redmires	25.6	13	1.97
Kinder Scout	16.5	8.7	1.90
Snake Pass	28.0	9.9	2.83
Little Moor	26.5	13.8	1.92
Flouch Inn	36.5	18.4	1.98
Rivelin	32.0	13.5	2.37
Upper Derwent			
A1	38.0	12.6	3.01
A2	32.0	12.6	2.54
B4	36.0	13	2.76
C8	29.5	10.9	2.71
D10	34.0	11.8	2.88
D11	34.5	12.6	2.73
E12	41.5	20.6	2.01
E13	32.5	11.8	2.75
E14	26.7	11.1	2.41
E15			

north. Later on, when the occlusion has stopped over the northern part of the study area, there is a negative correlation with altitude, mainly because the occlusion and its rain are some distance north of the highest ground in the area, but also because the system is now stationary. The evidence suggests that there is an 'orographic' component in the first half of the storm, to about 0200, this being shown by positive rainfall-altitude correlations (especially hours ending 2100, 0100, 022). This evidence seems to be confirmed by comparison of Gauge:Radar ratios (see section 6.5); during the 'orographic' rainfalls the ratios tend to be higher since low level enhancement is not detected by the radar. Later rainfall, generated at higher altitude is detected more accurately. Even from the hour total maps it is clear that two separate rain cells were involved: the first cell appears on figure 6.5d (2400) in the south and develops into an extensive area of rain as it moves north over Kinder Scout and then Bleaklow. Rainfall intensities increase greatly by 0100: since the radar detects this development, this suggests the triggering of convectional instability as the system moves north (feeder clouds may also have been created at low altitudes, but these might not have been detected by the radar - see later comments on gauge records). The second cell appears on the 0100 map in the south-east; by 0200 it has also moved north and intensified over the higher ground. Both cells become incorporated into the stationary band of rain in the north and although the intensities decline somewhat (see later comments on the 15-minute maps), the hour total remain high simply because the rain remains in one place. Later, as the occlusion begins to slide south-east one major cell is activated, perhaps through the influence of the higher ground to the north of Sheffield; this cell is just evident in the north-east of the study area (particularly on figure 6.6 which shows the total storm

rainfall estimated by the radar). Over Sheffield and Barnsley, beyond our mapped area, there were total falls of up to 70 mm.

The maps given on figure 6.7 are the individual radar scans from which the hour totals were summed. The maps show the equivalent hourly intensities for each pixel. Isohyets have been added to emphasise the higher intensity of the cells as they move over the higher ground. It is clear from all these maps, as well as from the wider radar hard-copies that fronts were activated as they moved over the southern Pennines, presumably by triggering convectional instability as noted above, although as noted below some low-level feeder clouds may also have been generated. Had the frontal system not stopped moving, a clear 'orographic' distribution of storm rainfall would have been evident for the whole storm, as well as for the first part, to 0200. Correlations between maximum altitude and rainfall intensity, as given on the figure 6.7 maps, were significant between 0017 and 0202. The first rain 'cell' appears in the south on the 2347 map and gradually intensifies as it moves over Kinder Scout, reaching intensities of 14 mm/hr by 0032 over Kinder and 12 mm/hr over Holme Moss. The second 'cell' appears on the 0047 map and again become more intense as it goes north, reaching 14 mm/hr by 0147 over Strines (to the east of the Upper Derwent). As the two cells gradually move north to become stationary, the rainfall/altitude correlation gradually falls, as expected. By 0302 intensities have declined as the occlusion moves over the lower northern parts of the study area (except for a small cell to the west of Holme Moss). As already noted, the occlusion became more active as it began to move south-east towards Sheffield and 15-minute intensities rose to 32 mm/hr although most of this rain fell beyond the mapped area.

Fig 6.6 : Total rainfall (radar estimate) for the storm of 9th/10th
September 1983.

25	26	24	22	25	23	20	20	19	20	20	20	17	19	17	15	15	17	18	18
23	24	24	24	24	20	24	24	20	22	22	22	18	19	17	16	15	15	18	25
23	27	24	26	25	25	24	27	26	23	21	23	22	21	23	20	20	21	24	30
14	17	25	26	29	25	25	25	17	28	23	21	24	22	19	20	22	21	29	33
11	14	21	28	29	28	26	23	27	30	23	25	20	20	20	20	25	25	28	43
7	9	15	23	10	21	25	23	13	28	24	25	21	16	17	21	26	32	39	46
6	6	11	16	15	17	18	10	10	21	16	14	16	18	20	17	25	33	40	51
6	6	8	12	14	13	14	14	16	17	13	12	14	18	20	22	22	30	44	56
7	7	9	10	14	13	13	13	15	14	11	11	14	21	20	30	29	35	44	52
4	5	6	10	8	9	11	13	13	14	11	10	11	20	26	30	34	44	44	60
3	4	4	6	6	8	11	14	11	11	10	11	12	13	24	33	33	43	45	50
1	1	2	5	5	6	9	11	11	9	8	9	9	13	21	30	30	28	36	44
1	1	2	4	4	5	10	11	14	8	6	6	8	10	14	24	23	21	24	34
1	1	2	3	4	4	6	12	15	11	5	6	6	7	11	17	21	19	24	28
1	1	2	3	4	4	5	11	13	12	6	7	6	8	11	18	16	18	17	21
1	1	1	3	4	4	5	9	12	10	6	5	6	8	10	14	12	13	13	13
1		1	1	4	4	4	6	10	10	7	6	7	8	9	9	9	8	10	11
1			2	4	4	4	5	8	8	5	5	4	7	7	7	5	6	7	8
1	1		2	3	4	5	5	7	6	6	4	3	5	5	5	6	5	7	5
1	1	1	3	10	7	6	7	6	5	5	3	3	4	5	5	5	4	5	

Fig 6.7 : 15-minute rainfall intensities (radar estimates) for the main period of the storm of 9th/10th September 1983. Figures are in millimetres per hour; the time given denotes the scan time.

2/2/83 2347

10/9/83 0002

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. 1 3 3 1 . 1 1 .
1 1 . . 1 3 5 1
. . 2 6 4 .
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1 . . 1 1 2 3 3 4 6 1 .
1 1 1 . 1 3 4 6 4 6 3 1 . . .
1 1 4 1 3 4 6 4 3 3 2 1 . . .
. 1 1 5 6 4 4 4 7 4 3 1 . . . 1 .
. . 1 1 1 4 5 3 6 8 2 . . . 2 4 1 4 .
. . 3 4 1 6 7 1 1 . . 3 6 1 1 2 .
. . 1 2 6 4 3 3 1 . . . 4 4 .
. 1 1 1 4 3 3 1 . 1 . . 2 2 .
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5 3 3 3 3 3 1 4 1 . . .
1 1 1 3 3 3 1 1 3 1 . . .
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1 . . 1 1 1 4 1 2 4 1 . . .
1 1 . . 1 1 5 5 1 3 3 1 . . .
. 1 1 1 2 3 3 5 5 3 2 3 . . . 1 . .
1 1 1 1 4 4 4 4 3 3 1 1 1 . 1 1 2 1 .
. 1 1 1 3 3 5 8 4 2 1 . 1 . 1 3 2 1 1
. . . . 3 8 6 3 2 1 1 . . 1 1 2 4 5 1
. . . . 1 4 3 2 2 . 1 1 1 . 1 3 1 1 3
. . . . 1 1 1 1 1 1 . . 1 1 2 2 1 1 .
. . . . . 1 1 1 . . 1 1 2 5 . .
. . . . . . . . 1 1 2 1 4 2 1 1
. . . . . . 3 1 5 3 4 2 1
. . . . . 1 3 1 2 2 1 2 1
. . . . . 1 . 1 1 1 . 1
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1 3 3 3 5 4 5 3 1 . . . 1
2 3 3 2 3 3 1 1 1 1 1 . . 1
1 1 . 1 3 3 1 1 4 3 2 . .
. . 1 1 1 4 2 1 1 4 3 2 . . .
. . 1 1 . 1 6 1 2 2 3 1 . . .
1 . 1 1 . 1 3 6 2 4 1 2 1 .
. 1 1 2 3 3 3 6 5 3 . 1 . . . 1 .
. 1 1 2 4 4 3 2 3 2 1 . 1 . 1 1 . 2 1 .
1 1 3 3 4 5 5 3 4 1 1 1 1 . . 1 3 3 1 1
. . 1 2 1 4 4 8 3 1 1 1 . 1 1 1 2 2 1 1
. . 1 4 6 2 1 1 1 2 1 1 1 1 1 1
. . 1 2 1 3 1 1 . 1 2 1 1 1 2 1 2
. . 1 . . 1 . . 1 1 2 3 5 6 1 1
. . . . . . . 2 2 2 3 6 3 3 .
. . . . . . 1 1 3 6 5 7 3 .
. . . . . 1 1 3 4 4 4 4
. . . . . 1 1 1 2 2 1 3
. . . . . 1 1 1 . 1 1 1
. . . . . 1 . . . 1 1 .
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3 4 2 1 1 1 . . 1 1 .
1 . . 3 3 . . 1 1 3 3 . .
1 3 . . 2 4 2 1 1 3 2 1 . .
2 2 4 1 1 1 2 2 1 1 3 3 2
2 1 2 1 2 4 4 4 3 1 1 2 1 . .
1 1 3 3 3 5 4 8 4 3 2 1 . . 1 . . .
. . 2 5 6 4 4 3 3 2 1 1 1 . . 1 1 1 1 .
1 1 1 2 7 5 7 3 4 4 . 1 1 . . 1 4 3 4 1
1 1 1 1 2 4 4 5 5 5 2 1 2 1 1 1 3 4 5 1
. . . . 1 1 3 1 3 3 4 3 6 8 3 1 3 1 1
. . . . 1 1 . 1 1 4 4 3 X 8 4 5 1 1
. . . . 1 1 1 . . 1 1 3 8 X 8 8 4 1
. . . . . 1 1 4 X X X 3 1
. . . . . 1 1 1 2 6 X X 3
. . . . . 1 . 1 1 5 6 X 8 1
. . . . . 1 1 2 5 6 5
. . . . . 1 1 . 1 2 4 4
. . . . . 1 . . . 1 1 1
. . . . . 1 . . . .
. . . . . 1 1 .

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1 . . 3 1 1 . 1 1 1 1 .
2 1 . 1 4 1 1 1 . 1 4 2 1 . .
5 5 1 2 3 3 1 1 . 1 3 3 3 . . .
1 4 1 2 5 4 1 2 1 . 1 1 4 . . . .
3 3 1 4 3 6 5 1 3 1 . . 1 1 . . 1
1 1 4 4 5 4 6 5 3 3 . . 1 . . 1 1 . .
. 1 3 5 6 5 5 8 5 3 1 1 . . . 1 3 3 1
. . . 1 3 3 1 3 6 5 3 1 2 1 1 3 2 3 6 1
1 . . . . 1 1 1 4 1 3 3 3 4 6 3 3 3 4 6
1 . . . . 1 . . 2 1 3 2 5 X X 6 3 4 4
1 1 . . . 1 . . 1 3 2 2 2 7 X X 6 6 4
. . . . . 3 3 3 3 6 8 8 4 6 8
. . . . . 1 1 3 3 6 7 8 1 6 6
. . . . . 1 1 3 1 4 5 5 4 4 4
. . . . . 1 . 2 2 5 3 3 2 4
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. . . 1 1 2 1 1 1 . 3 5 1
4 2 1 1 1 . 1 1 . . 3 4 6 1 .
3 3 2 3 3 1 1 5 1 . 1 3 5 1 . 1
1 1 2 3 7 3 1 1 3 1 . 1 2 1 . . .
1 1 4 4 5 3 1 3 1 1 1 . 2 2 . . 1 1 .
1 1 1 3 5 3 3 2 2 1 1 2 2 1 1 1 4 1 . 1
. 1 1 1 1 1 3 5 3 1 1 1 1 3 4 1 3 1 1 1
. . . . . 1 3 3 2 1 1 3 6 7 7 3 2 3 3
1 . . . . 1 2 2 1 1 2 7 8 7 3 3 4
1 1 . . . 1 1 1 1 1 4 6 8 8 8 3 3
. . . . 1 1 1 1 1 4 6 7 8 5 4
. . . . 1 1 1 1 1 6 7 4 4
. . . 1 2 2 2 6 6 4 3 3
1 . 1 1 1 1 2 4 5 3 2
. 1 . . . 1 2 2 4 2 1
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1 2 1 3 1 1 3 3 1 . . . 1 1 . .
1 2 5 5 2 . 1 1 2 1 . 1 1 1 1 1 .
1 1 3 5 7 5 1 3 2 2 . . 1 3 1 1 1 1 .
1 1 1 3 2 6 5 3 3 1 2 4 3 1 1 2 4 3 1 .
1 1 1 1 1 1 4 4 2 1 1 3 3 1 2 3 4 6 1 1
1 1 2 . . 1 1 1 3 1 1 1 1 6 5 4 4 4 3 3
. 1 2 6 1 . . 1 2 2 . 1 3 4 8 5 3 4 5 4
. . 1 1 1 1 1 1 1 3 1 1 1 8 8 6 4 3 4 4
. . . . . 1 1 1 1 3 8 8 6 4 4 3
. . 1 1 . 1 1 4 7 7 7 4 2
. . 1 1 1 3 4 6 6 5 2
. . . . 1 . 1 4 5 4 4 1
. . . . . 2 3 3 3 3
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[illegible]

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7 6 3 4 4 1 1 1 . . . 1 1 6 3 . . . 1
5 5 7 6 4 3 3 2 1 . . . 1 3 6 3 2 2 1 1 1
6 5 4 6 3 3 4 1 1 3 1 3 6 6 6 4 2 1 1 1
5 4 X 8 X 3 7 5 0 7 3 2 5 5 4 4 4 1 2 3
7 8 8 X 8 7 6 6 6 X 7 6 5 5 4 4 4 5 7 4
1 2 3 5 5 5 5 6 8 7 6 8 6 5 6 5 4 4 4 6
. 1 . 1 1 3 1 2 8 X 5 4 5 6 5 4 6 5 4 6
. . . . 1 . . . 1 4 5 4 3 6 5 2 4 4 6 6
. . . . . . . . 2 2 4 4 3 3 4 4 6 X
. 1 . . . . 1 . . . 1 4 2 2 3 5 6 8
. . . . . . . . 1 1 1 1 1 4 4 5
. . . . . . . . 1 . 1 1 1 1 2 3
. . . . . . . . . 1 2 4
. . . . . . . . . 1 1 1
. . . . . . . . . 1 1
. . . . . . . . . 1 2 1
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2 5 3 3 3 2 1 . . . 1 1 1 3 5 4 2 1 1 1 1
3 3 1 1 2 1 2 1 1 1 2 2 2 4 4 1 1 1 1
6 6 4 2 2 1 1 1 3 3 3 4 3 6 6 2 3 3 1 2
7 5 8 5 3 1 2 4 4 4 4 5 6 6 4 6 4 2 2 1
4 4 5 6 8 3 2 5 3 X 5 6 4 5 4 5 6 6 4 6
1 1 3 5 5 3 3 3 8 X X 8 5 4 4 5 8 8 X X
. . . 1 1 1 1 3 4 7 5 7 8 5 3 1 4 7 X X
. . . . . 1 3 3 2 1 3 4 3 1 1 3 6 X
. . . . . . 1 1 1 1 3 3 2 1 2 3 5
. . . . . . 1 . . 1 3 3 1 1 3 3 3
1 . . . . 1 1 1 1 1 1 1 1 1 1 1 2
. . . . . 1 . . . . 1 . . 1 1
. . . . . . . . . 1 1 1 1
. . . . . . . . . 1 1 1 1
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. . . . . . . . . 1 1 1
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[illegible]

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Table 6.3 Output for the Snake Pass data logger : 9 September 1983

TIME (GMT)	RAINFALL (MM)	INTENSITY (MM/HR)
21:12:39	0.50	
21:59:09	0.50	0.78
21:56:15	0.50	4.92
22:07:01	0.50	2.29
22:45:28	0.50	0.78
23:42:39	0.50	0.52
23:46:24	0.50	8.00
00:32:20	0.50	0.65
00:44:31	0.50	2.46
00:48:45	0.50	7.11
00:51:05	0.50	12.80
00:52:58	0.50	16.00
00:55:18	0.50	12.80
00:57:11	0.50	16.00
01:01:52	0.50	6.40
01:05:09	0.50	9.14
01:09:50	0.50	6.40
01:13:35	0.50	8.00
01:15:28	0.50	16.00
01:17:48	0.50	12.80
01:19:41	0.50	16.00
01:22:30	0.50	10.66
01:29:32	0.50	4.27
01:40:46	0.50	2.66
01:45:00	0.50	7.11
01:48:45	0.50	8.00
01:52:58	0.50	7.11
01:57:11	0.50	7.11
02:00:28	0.50	9.14
02:04:13	0.50	8.00
02:07:01	0.50	10.67
02:09:50	0.50	10.66
02:13:07	0.50	9.14
02:17:29	0.50	7.11
02:26:15	0.50	3.37
02:37:58	0.50	2.56
02:51:33	0.50	2.21

03:08:54	0.50	1.73
03:31:52	0.50	1.31
J3:45:28	0.50	2.20
03:55:46	0.50	2.91
05:25:18	0.50	
05:46:52	0.50	1.39
05:53:26	0.50	4.57
05:57:39	0.50	7.11
06:02:20	0.50	6.40
06:07:01	0.50	6.40
06:11:43	0.50	6.40
06:16:24	0.50	6.40
06:20:37	0.50	7.11
06:23:54	0.50	9.14
06:30:28	0.50	4.57
06:37:30	0.50	4.27
06:45:56	0.50	3.56
07:18:45	0.50	0.91
07:39:22	0.50	1.46

Total for rainfall day 9-9-83 : 28.00 mm

Table 6.4 Output for the Little Moor data logger : 9 September 1983

TIME (GMT)	RAINFALL (MM)	INTENSITY (MM/HR)
21:53:06	0.50	
22:00:00	0.50	4.57
22:07:01	0.50	4.27
22:39:50	0.50	0.91
22:48:16	0.50	3.56
00:33:16	0.50	
00:57:39	0.50	1.23
01:17:48	0.50	1.49
01:28:35	0.50	2.78
01:53:54	0.50	1.19
01:58:07	0.50	7.11
02:01:52	0.50	8.00
02:05:37	0.50	8.00
02:08:54	0.50	9.14
02:11:43	0.50	10.67
02:14:03	0.50	12.80
02:15:28	0.50	21.33
02:16:52	0.50	21.33
02:18:45	0.50	16.00
02:20:37	0.50	16.00
02:22:58	0.50	12.80
02:25:46	0.50	10.67
02:29:31	0.50	8.00
02:32:48	0.50	9.14
02:36:05	0.50	9.14
03:38:26	0.50	12.80
02:41:43	0.50	9.14
02:47:48	0.50	4.92
02:54:50	0.50	4.27
03:00:56	0.50	4.92
03:10:46	0.50	3.05
03:19:41	0.50	3.37
03:27:11	0.50	4.00
03:35:37	0.50	3.56
03:45:00	0.50	3.20
04:00:28	0.50	1.94

04:15:00	0.50	2.06
04:44:03	0.50	1.03
04:55:46	0.50	2.56

05:05:09	0.50	3.20
05:15:28	0.50	2.91
05:25:46	0.50	2.91
05:36:33	0.50	2.78
05:43:35	0.50	4.27
05:51:33	0.50	3.76
05:58:07	0.50	4.57

06:08:26	0.50	2.91
06:18:16	0.50	3.05
06:30:56	0.50	2.37
06:40:46	0.50	3.05
06:51:33	0.50	2.78

07:06:33	0.50	2.00
07:42:39	0.50	0.83

Total for Rainfall Day 9-9-83: 26.50 mm

Table 6.5 Output for the Flouch Inn data logger : 9 September 1983

TIME (GMT)	RAINFALL (MM)	INTENSITY (MM/HR)
21:24:22	0.50	
22:03:45	0.50	0.76
22:10:18	0.50	4.57
22:22:30	0.50	2.46
22:48:45	0.50	1.14
22:53:26	0.50	6.40
23:35:57	0.50	0.71
00:11:15	0.50	0.84
00:37:58	0.50	1.12
00:43:35	0.50	5.33
00:52:30	0.50	3.37
01:20:09	0.50	1.08
01:45:56	0.50	1.16
01:55:18	0.50	3.20
02:04:13	0.50	3.37
02:10:18	0.50	4.92
02:17:20	0.50	4.27
02:23:54	0.50	4.57
02:30:56	0.50	4.27
02:34:41	0.50	8.00
02:37:58	0.50	8.00
02:37:58	0.50	9.14
02:41:43	0.50	8.00
02:45:00	0.50	9.14
02:47:20	0.50	12.80
02:49:41	0.50	12.80
02:51:05	0.50	21.33
02:53:26	0.50	12.80
02:55:18	0.50	16.00
02:59:03	0.50	8.00
03:02:20	0.50	9.14
03:06:05	0.50	8.00
03:08:26	0.50	12.80
03:10:18	0.50	16.00
03:11:43	0.50	21.33
03:13:35	0.50	16.00
03:15:28	0.50	16.00

6.6 Conclusions

- i) Analysis of one case study storm suggests that rainfall radar is capable of detecting orographic rainfall when convective instability has been triggered. The radar is also reasonably accurate during the occlusion-based rainfall where, again, the clouds generating the rainfall were thought to be quite high. The radar was not so accurate during the period when it is believed that low-level feeder clouds were being produced as the rain cells moved northwards over the southern Pennines.
- ii) In almost all cases the radar was underestimating rainfall intensities, this being most serious during the period when rain cells were moving over the study area. The radar clearly underestimated high rainfall intensities over the hills, but did better with the high-intensity cells developed in association with the occlusion. Gauge totals for the storm were underestimated by 15 to 20 mm over the hills.
- iii) The decoding of radar hard-copy is a tedious business; it would clearly aid further studies of this sort if the original digital data could be made available.
- iv) The use of data logger raingauges provides data in an immediately usable form and is much preferable to the autographic charts which require decoding or digitising before the data can be analysed.
- v) The radar provides quite stable rainfall estimates, even when one or two scans are 'missing' in any given hour. It is clear

that if the low-level rainfall intensity enhancement can be monitored, then radar will provide a very valuable aid to distributed runoff modelling in the upland environment. As it stands radar is potentially less valuable since it can severely underestimate high rainfall intensities - the most crucial elements in any flood forecast. This further suggests that the use of telemetering gauges would most definitely be preferable in the Pennine uplands, if the radar performance displayed here is proved to be more generally typical.

- v) The scale of the orographic rainfall pattern revealed in this case study confirms that the Upper Derwent (15 km²) was too small to displat anything other than local variations in the rainfall distribution. A much wider scale of study would seem appropriate. This would make the logistics of the fieldwork much simpler, since road access to each gauge could be ensured, even for the highest gauges as at Snake Pass. Remote sites, such as Kinder Scout, would be best served using a data logger gauge.

Acknowledgement

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Chapter 7 Modelling the Effect of Spatial Variations of Rainfall on the Sotrm Hydrograph

7.1 Introduction

Until the last few years, the science of hydrology has been dominated by models, such as the Unit Hydrograph, which incorporate simple linear equations. Whilst this may represent a gross simplification of reality, the continued use of such models is justified on two grounds: firstly, because these models can often provide very accurate hydrograph predictions (at least for gauged catchments); and secondly, because the use of such models may be for purposes other than prediction. Most of the use of such models may be for purposes other than prediction. It was originally intended to use HEC1, a physically-based distributed model, for the simulation experiments. However, despite some early use of the model, it did not prove possible to calibrate the model satisfactorily. The advantage of HEC1 is that it can be applied to ungauged catchments, and even on gauged catchments such as the Upper Derwent, most of the parameters are fixed using physical characteristics of the basin, and optimisation follows. One of its disadvantages is that there are so many components of the model that it becomes difficult to assess model performance. For example, in order to run simulations using HEC1, we must first calibrate the model to an acceptable level of accuracy, and then run the simulations. However, we do not necessarily know if the model is making accurate predictions because all the parameters are set correctly, or whether this is simply by chance. Thus, when we come to alter input values 'experimentally' (eg. changing the amount and spatial distribution of storm rainfall), we may not know the true effect the input distribution because this may be masked by the

distribution of other parameter values, such as infiltration capacity or channel velocities. On the Upper Derwent we can only calibrate for the outflow hydrograph and there are no internal checks, and this must introduce some uncertainty into any predictions. Model complexity should not be confused with accuracy. For this reason we have chosen here to use a very simple approach - the time-area model - in order to investigate the run-off system at a much simpler, but perhaps rather more tangible, level.

We can identify three areas for model use:

- for forecasting
- for teaching
- for research

Most runoff models have been designed as forecasting tools and their use for other purposes has, until recently, been generally a later and fortuitous event. It is self-evident that forecasting models are designed to make successful predictions; thus, calibration and verification are crucial elements in their development. The choice of model type is dictated by a simple principle: the simplest model which will provide acceptable accuracy in solving the defined problem would be adopted. More complex models may be more versatile but a black box model may provide better and cheaper predictions. However, recently, more important 'research' uses of runoff models have become evident: many models, given their theoretical basis, also offer much potential for experimental work, substituting the computer terminal for the field site. We wish to stress this aspect of model use since such theoretical

'exploration' can often lead to significant advances in our understanding of how the physical system operates and how better to model and monitor it. For example, Konikow and Patten (1985), in discussing process-based modelling of groundwater systems, make several comments about the value of simulation modelling as an aid to formulating an improved model of the aquifer. For example, the important influences of temperature differences and aquifer discontinuities on flow in the Madison aquifer (Wyoming, USA) were only recognised and documented as a result of model analysis. Konikow and Patten (1985, p239) note that

"Although it could be argued that the importance of these influences could have been (or should have been) recognised on the basis of hydrogeological principles without the use of a simulation model, the fact is that none of the earlier published studies of this aquifer system indicated that these factors were of major significance. The difference from earlier studies arose from the quantitative hypothesis-testing role of the model."

Differences between observed and predicted output led them to look for reasons for these inconsistencies, and to develop a three-dimensional approach so as to better model the system. Similar experience with another groundwater flow model enabled them to propose an improved measurement system for sampling the movement of a pollution plume through the aquifer.

The use of a theoretically-based simulation model can greatly improve our understanding of the physical system, highlighting properties of the system which should be predictable but which, given the complexity of the real world, only become apparent when using a simulation model. Whilst we may be able to write theoretical statements to describe the operation of the system, once we have more than two inputs and/or

parameters to consider, we cannot mentally imagine their combined effect on model output (ie. we can do no more than conceptualise 'contour' surfaces). Nor can field research necessarily be much help, since extensive, controlled experiments in the field are prohibitively expensive, or logistically very arduous (as in this study) and may be rendered impossible by uncontrollable climatic variations. Even using a simple simulation model, we can systematically improve our understanding of complex environmental systems in a way which has not been previously possible. Thus, here, we supplement the results of empirical research in the field with 'theoretical' controlled experimentation using a simulation model .

7.2 Flood hydrographs using the time-area method

It is often possible to portray a complex system using simple linear equations. Whilst this may represent a gross simplification of reality, the exercise is still valuable in that it forces us to try to model the theoretical basis of the system. Using our simple model we can then investigate the role of individual variables within the system in a controlled manner. In complex environmental systems many variables must be considered: since we cannot easily set up lots of controlled field experiments to find out how a single factor influences a process, a simulation model helps us to investigate such controls theoretically. Once we have an idea of how the system is structured, we may then progress to more complex models. As will be seen in the examples below, even at this stage our models must be physically realistic, but because the system is greatly simplified, with process mechanics not correctly modelled, they remain black box models. Such models balance a relatively simple structure against grossly simplified process mechanics therefore. We argue here that the use of the time-area model is still worthwhile, despite its simplicity, for the insights it produces, as well as for its somewhat surprising accuracy.

Consider the way in which a flood hydrograph is produced at the outlet of a drainage basin. The basin has two components: a certain proportion of the rainfall input is converted to runoff on the hillslopes; this runoff then enters the stream and is routed through the channel network to the basin outlet. Let us first model the conversion of rainfall into runoff. In 1850, an Irish land drainage expert called Mulvaney first suggested an extremely simple method of predicting runoff, known as the rational method:

$$Q = c * i * A$$

where Q is the discharge, i is the rainfall intensity, A is the catchment area, and c is a runoff coefficient. c has a range between 0 and 1, representing the fraction of rainfall which is converted into runoff. c may be as low as 0.01 in very permeable basins, and as high as 0.9 in impermeable urban catchments. Clearly the formula is extremely simple: no reference is made to actual runoff processes on the catchment hill-slopes, and the runoff coefficient is considered constant through time. This latter point underlines the theoretical weakness of all the 'traditional' runoff models: namely that the runoff response to rainfall is linear, with the effects of antecedent conditions, storages and thresholds not being considered. the time-area method is a very simple method of hydrograph prediction seldom used today by engineers for flood prediction in large rural catchments, although the method is still the basis of some commonly-used urban flood models, such as the TRRL model.

In the time-area method, a drainage basin is divided into zones on the basis of isochrones - a line of equal travel time along the channel, usually set at one hour intervals. Thus the runoff produced in the area nearest the basin outlet (A_1) takes one hour to reach the basin outlet; runoff from area A_2 takes two hours to reach the outlet, and so on. Thus, if we have a series of hourly rainfall totals ($i_1, i_2, i_3 \dots i_n$), the total discharge for any given hour will be:

$$Q_t = c_1 * A_1 * i_{(t-1)} + c_2 * A_2 * i_{(t-2)} + c_n * A_n * i_{(t-n)}$$

To apply this formula to a real basin, some idea of the length of each time zone (measured along the stream channel) may be obtained from the formula suggested by Kirpich (1940):

$$L = (T_c * S^{1.25}) / 0.00025$$

where T_c is the time of concentration (usually one hour), S is the channel gradient (m.m-1), and L is the length of each time-area subunit (m). For the Upper Derwent, Kirpich's formula showed that all the low order tributaries have travel times well within one hour. Thus travel time is limited only by the routing of the flood wave along the main stream channel (and also by the time delay for hillslope runoff to reach the stream, of course). Correctly, the basin should be divided up into sub-basins on the basis of isochrones, and, to input rainfall totals into each sub-basin (if there is more than one gauge), and a series of weights is used to allocate rainfall from different gauges to a given area. In the Upper Derwent, plotting the isochrones along the main stream provides three divisions: these divisions coincided so closely with the Thiessen polygon map of areas 'belonging' to each rain gauge in the catchment (see figure 5.10) that it was decided to define the sub-basin areas by amalgamating polygons rather than on the basis of tributary basins. The resulting sub-area map is shown on figure 7.1. This made the task of writing the runoff model program much easier since it avoided the need to use weights. One generation of the BASIC program which was developed is given on figure 7.2. It is admitted that the areas are slightly different from what would otherwise have been the case, but given the other simplifications made in this model, this use of Thiessen polygons seems allowable. After all, the use of Kirpich's

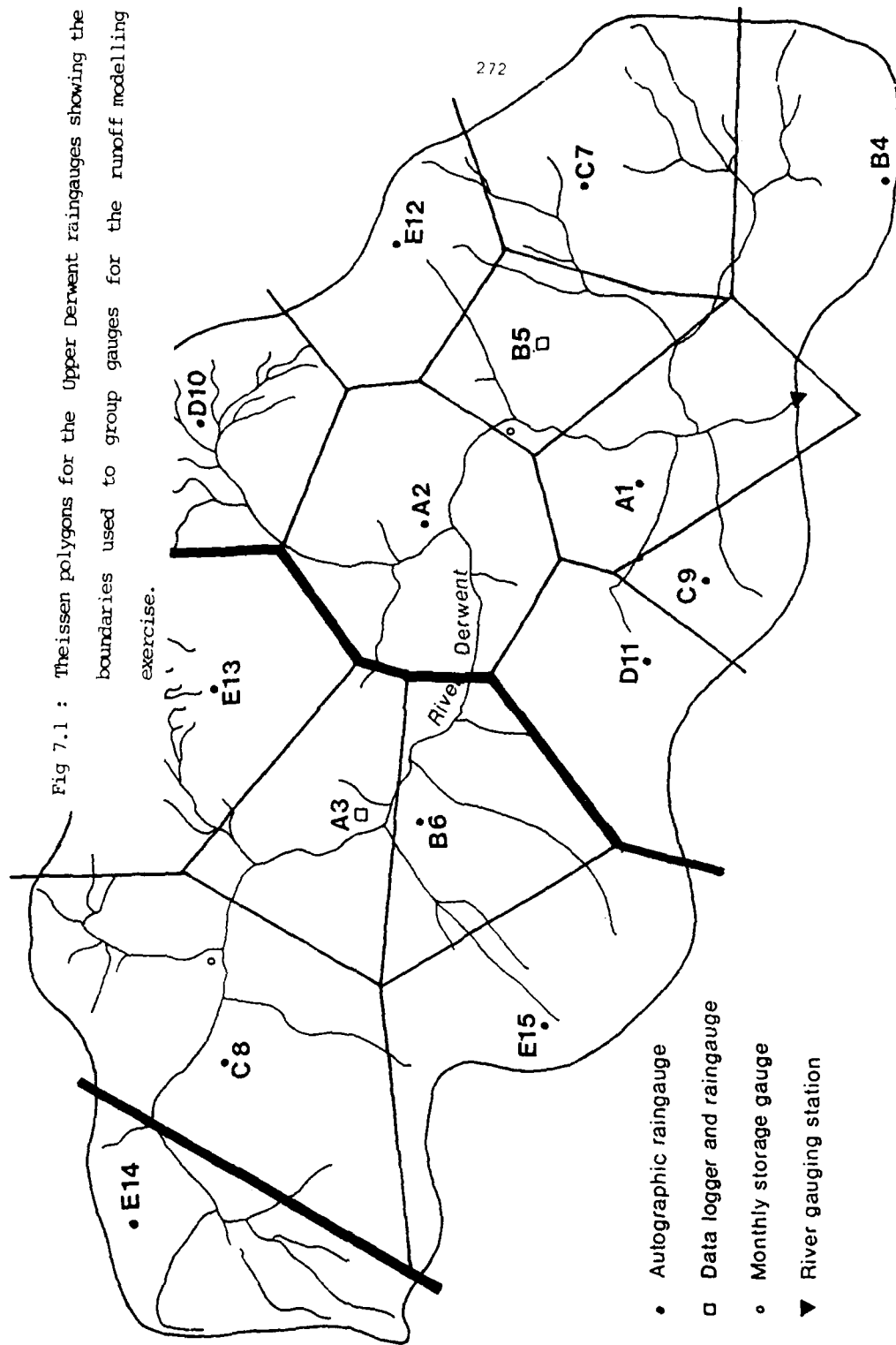


Fig 7.2 : A version of the LASIC program for the time-area hydrograph prediction model.

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1000  GO TO 1001, 1002, 1003, 1004, 1005, 1006, 1007, 1008, 1009, 1010, 1011, 1012, 1013, 1014, 1015, 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1027, 1028, 1029, 1030, 1031, 1032, 1033, 1034, 1035, 1036, 1037, 1038, 1039, 1040, 1041, 1042, 1043, 1044, 1045, 1046, 1047, 1048, 1049, 1050, 1051, 1052, 1053, 1054, 1055, 1056, 1057, 1058, 1059, 1060, 1061, 1062, 1063, 1064, 1065, 1066, 1067, 1068, 1069, 1070, 1071, 1072, 1073, 1074, 1075, 1076, 1077, 1078, 1079, 1080, 1081, 1082, 1083, 1084, 1085, 1086, 1087, 1088, 1089, 1090, 1091, 1092, 1093, 1094, 1095, 1096, 1097, 1098, 1099, 1100, 1101, 1102, 1103, 1104, 1105, 1106, 1107, 1108, 1109, 1110, 1111, 1112, 1113, 1114, 1115, 1116, 1117, 1118, 1119, 1120, 1121, 1122, 1123, 1124, 1125, 1126, 1127, 1128, 1129, 1130, 1131, 1132, 1133, 1134, 1135, 1136, 1137, 1138, 1139, 1140, 1141, 1142, 1143, 1144, 1145, 1146, 1147, 1148, 1149, 1150, 1151, 1152, 1153, 1154, 1155, 1156, 1157, 1158, 1159, 1160, 1161, 1162, 1163, 1164, 1165, 1166, 1167, 1168, 1169, 1170, 1171, 1172, 1173, 1174, 1175, 1176, 1177, 1178, 1179, 1180, 1181, 1182, 1183, 1184, 1185, 1186, 1187, 1188, 1189, 1190, 1191, 1192, 1193, 1194, 1195, 1196, 1197, 1198, 1199, 1200, 1201, 1202, 1203, 1204, 1205, 1206, 1207, 1208, 1209, 1210, 1211, 1212, 1213, 1214, 1215, 1216, 1217, 1218, 1219, 1220, 1221, 1222, 1223, 1224, 1225, 1226, 1227, 1228, 1229, 1230, 1231, 1232, 1233, 1234, 1235, 1236, 1237, 1238, 1239, 1240, 1241, 1242, 1243, 1244, 1245, 1246, 1247, 1248, 1249, 1250, 1251, 1252, 1253, 1254, 1255, 1256, 1257, 1258, 1259, 1260, 1261, 1262, 1263, 1264, 1265, 1266, 1267, 1268, 1269, 1270, 1271, 1272, 1273, 1274, 1275, 1276, 1277, 1278, 1279, 1280, 1281, 1282, 1283, 1284, 1285, 1286, 1287, 1288, 1289, 1290, 1291, 1292, 1293, 1294, 1295, 1296, 1297, 1298, 1299, 1300, 1301, 1302, 1303, 1304, 1305, 1306, 1307, 1308, 1309, 1310, 1311, 1312, 1313, 1314, 1315, 1316, 1317, 1318, 1319, 1320, 1321, 1322, 1323, 1324, 1325, 1326, 1327, 1328, 1329, 1330, 1331, 1332, 1333, 1334, 1335, 1336, 1337, 1338, 1339, 1340, 1341, 1342, 1343, 1344, 1345, 1346, 1347, 1348, 1349, 1350, 1351, 1352, 1353, 1354, 1355, 1356, 1357, 1358, 1359, 1360, 1361, 1362, 1363, 1364, 1365, 1366, 1367, 1368, 1369, 1370, 1371, 1372, 1373, 1374, 1375, 1376, 1377, 1378, 1379, 1380, 1381, 1382, 1383, 1384, 1385, 1386, 1387, 1388, 1389, 1390, 1391, 1392, 1393, 1394, 1395, 1396, 1397, 1398, 1399, 1400, 1401, 1402, 1403, 1404, 1405, 1406, 1407, 1408, 1409, 1410, 1411, 1412, 1413, 1414, 1415, 1416, 1417, 1418, 1419, 1420, 1421, 1422, 1423, 1424, 1425, 1426, 1427, 1428, 1429, 1430, 1431, 1432, 1433, 1434, 1435, 1436, 1437, 1438, 1439, 1440, 1441, 1442, 1443, 1444, 1445, 1446, 1447, 1448, 1449, 1450, 1451, 1452, 1453, 1454, 1455, 1456, 1457, 1458, 1459, 1460, 1461, 1462, 1463, 1464, 1465, 1466, 1467, 1468, 1469, 1470, 1471, 1472, 1473, 1474, 1475, 1476, 1477, 1478, 1479, 1480, 1481, 1482, 1483, 1484, 1485, 1486, 1487, 1488, 1489, 1490, 1491, 1492, 1493, 1494, 1495, 1496, 1497, 1498, 1499, 1500, 1501, 1502, 1503, 1504, 1505, 1506, 1507, 1508, 1509, 1510, 1511, 1512, 1513, 1514, 1515, 1516, 1517, 1518, 1519, 1520, 1521, 1522, 1523, 1524, 1525, 1526, 1527, 1528, 1529, 1530, 1531, 1532, 1533, 1534, 1535, 1536, 1537, 1538, 1539, 1540, 1541, 1542, 1543, 1544, 1545, 1546, 1547, 1548, 1549, 1550, 1551, 1552, 1553, 1554, 1555, 1556, 1557, 1558, 1559, 1560, 1561, 1562, 1563, 1564, 1565, 1566, 1567, 1568, 1569, 1570, 1571, 1572, 1573, 1574, 1575, 1576, 1577, 1578, 1579, 1580, 1581, 1582, 1583, 1584, 1585, 1586, 1587, 1588, 1589, 1590, 1591, 1592, 1593, 1594, 1595, 1596, 1597, 1598, 1599, 1600, 1601, 1602, 1603, 1604, 1605, 1606, 1607, 1608, 1609, 1610, 1611, 1612, 1613, 1614, 1615, 1616, 1617, 1618, 1619, 1620, 1621, 1622, 1623, 1624, 1625, 1626, 1627, 1628, 1629, 1630, 1631, 1632, 1633, 1634, 1635, 1636, 1637, 1638, 1639, 1640, 1641, 1642, 1643, 1644, 1645, 1646, 1647, 1648, 1649, 1650, 1651, 1652, 1653, 1654, 1655, 1656, 1657, 1658, 1659, 1660, 1661, 1662, 1663, 1664, 1665, 1666, 1667, 1668, 1669, 1670, 1671, 1672, 1673, 1674, 1675, 1676, 1677, 1678, 1679, 1680, 1681,
```

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430 DIM C7(14): FOR I = 1 TO N: READ
    C7(I)
440 DATA 0.,.2,0.,1.5,1.6,.5,.5,6
    .9,3.5,2.6,4,4,.8: NEXT I
450 DIM C8(14): FOR I = 1 TO N: READ
    C8(I)
460 DATA 0,0.2,0.1,1.8,1.4,0.6,
    0.5,6.3,6.4,4.2,2.2,2.9,3.5,1:
    NEXT I
470 DIM C9(14): FOR I = 1 TO N: READ
    C9(I)
480 DATA 0.0,1,0.2,1.8,1.4,0.2,
    1.7,8.1,6.7,.3,1.9,4.5,3.5,
    0.9: NEXT I
490 DIM D(14): FOR I = 1 TO N: READ
    D(I)
500 DATA 0,0.1,0.1,0.7,2.2,0.7,
    0.8,2.5,11.4,6.4,2.1,2.5,3.5,
    1.2: NEXT I
510 DIM D1(14): FOR I = 1 TO N: READ
    D1(I)
520 DATA 0,0.1,0.2,1.8,1.4,0.2,
    1.7,8.1,6.7,3.3,1.9,4.5,3.9,
    0.9: NEXT I
530 DIM E2(14): FOR I = 1 TO N: READ
    E2(I)
540 DATA 0,0.2,0.1,7,1.5,0.5,0,
    8,7,16.9,3.5,2.4,4.9,2.9,0.8
    : NEXT I
550 DIM E3(14): FOR I = 1 TO N: READ
    E3(I)
560 DATA 0.1,0.1,0,1.2,1.3,0.7,
    1.5,2.6,10.2,5.4,1.5,3.2,3.4,
    1: NEXT I
570 DIM E4(14): FOR I = 1 TO N: READ
    E4(I)
580 DATA 0,0.1,0.1,1.2,1,0.6,0,
    5.5,7.5,7.4,1.8,2.7,2.6,0.7:
    NEXT I
590 DIM E5(14): FOR I = 1 TO N: READ
    E5(I)
600 DATA 0,0.1,0.2,1.3,0.7,1,8,
    5.1,4.1,8,2.5,3,1.2: NEXT I
610 DIM R1(N): FOR I = 1 TO N: READ
    R1(I)
620 DATA 0,0,0,.31,.13,.06,1.13
    ,2.07,1.63,0.56,0.6,2.56,2.3
    8,0.19: NEXT I
630 DIM R2(N): FOR I = 1 TO N: READ
    R1(I)
640 DATA 0,0,0,0.59,.06,0.0,0.82,
    2.19,1.63,0.56,0.6,2.56,2.38
    ,.19: NEXT I
650 DIM R3(N): FOR I = 1 TO N: READ
    R3(I)
660 DATA 0,0,0,.59,.13,0,.19,2,
    30,1.63,1.32,.56,2.47,2.68,0
    .19: NEXT I
670 DIM R4(N): FOR I = 1 TO N: READ
    R4(I)
680 DATA 0,0,0,0.66,0.19,0.0,0.31
    ,3.44,3.5,3,1.03,3.72,4.5,.2
    5: NEXT I
690 DIM R5(N): FOR I = 1 TO N: READ
    R5(I)
700 DATA 0,0,0,1.15,0,0,.25,2.3
    2,1.38,.72,.13,2,3,16,.19: NEXT
    I

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```

710 DIM R6(N): FOR I = 1 TO N: READ
  R6(I)
720 DATA 0,0,0,1,47,0,0,25,2,3
  1,1,47,2,1,1,1,1,68,3,47,31
  : NEXT I
730 DIM R7(N): FOR I = 1 TO N: READ
  R7(I)
740 DATA 0,0,0,125,7,25,0,1,
  1,2,1,2,04,1,88,1,44,1,64,3,6
  3,1,44: NEXT I
749 REM SNAKE DATA LOGGER
750 DIM S(N): FOR I = 1 TO N: READ
  S(I)
760 DATA 0,0,0,1,5,1,1,2,5,7,4,
  5,2,0,2,4,5,1: NEXT I
800 REM SUM RUNOFF FOR EACH TIM
  E AREA
802 X1 = D + A2 + E2 + D1 + C9 +
  A1 + B5 + C7 + B4
804 X2 = C8 + E5 + B6 + A3 + E3
806 X3 = E4
810 DIM Q1(N + 2): DIM Q2(N + 2)
  : DIM Q3(N + 2)
820 FOR I = 1 TO N
830 Q1(I) = S(I) * C * X1
840 Q2(I) = S(I) * C * X2
850 Q3(I) = S(I) * C * X3
860 Q1(I) = Q1(I) * 1000: Q2(I) =
  Q2(I) * 1000: Q3(I) = Q3(I) *
  1000
870 NEXT I
873 DIM G(54)
875 REM INPUT RUNOFF PREDICTION
  USING ALL GANGES
880 FOR I = 1 TO N
885 READ G(I)
890 DATA 0,079,0,079,0,079,0,65
  2,1,192,1,895,1,816,2,545,5,66
  6,4,582,2,434,2,513,2,749,1,
  823,0,605
895 NEXT I
900 REM CONVOLUTE HYDROGRAPH
901 PRE I
902 PRINT "SNAKE LOGGE"
903 PRINT "*****"
905 TI = 18
910 DIM Q4(54)
915 Q4(1) = QB: Q4(2) = QB: Q4(3) =
  QB
920 Q1(15) = Q: Q1(16) = Q: Q2(15) =
  Q
925 FOR I = 4 TO N + 2
930 Q4(I) = Q1(I) + Q2(I - 1) + Q
  3(I - 2)
935 Q4(I) = INT (Q4(I) / 3600 +
  QB * 1000) / 1000
940 T = TI + I: IF T > 24 THEN T =
  TI + I - 24
950 PRINT "T=";T;" QP=";Q4(I) -
  1;"QO=";Q(I - 2)
960 T = TP + (3600 * Q4(I - 2))
  : T = TC + (3600 * Q(I - 2))
965 NEXT I
980 PRINT
1000 FOR I = 3 TO N
1010 Z = Z + (Q - I - 2) - Q4(I - 2)
  : I = (Q(I - 2) - Q4(I - 2))
1015 NEXT I
1020 PRINT "Z = ";Z
1030 PRINT "C = ";C
1040 PRINT "TQP=";TP:"TQO=";TO
1050 PRINT "DIFF = ";TP - TO

```

formula is a large simplification in itself, so slight differences in sub-areas may not be important. In any case, the definition of basin areas on the map is subject to some error, especially in an area of high drainage density and relatively inaccurate mapping such as the Pennines (Burt and Oldman, 1985). From an operational point of view, this 'polygon' method was most valuable, for the reason already stated. Note, finally, that the rainfall is delayed by two hours: this represents the time-delay of hillslope runoff reaching a stream channel and was determined by trial-and-error.

Before progressing to the results, two other points must be discussed: calibration and accuracy.

1) Calibration

In any model, the specific relationship between general model form and the physical system being studied is gained via the parameters; their accuracy determines the goodness of fit between the model output and the recorded output. In this model there is only one parameter, 'c'. Two possible routes to setting the parameter value were available: either we could use recorded hydrographs to calculate Runoff Percent/ (ROP = the percentage of rain as runoff. The runoff percent for the 9.9.83 storm hydrograph discussed below is 20.9%. This would give us a first estimate of 'c' of 0.209). The other method of setting parameter values is to perform some form of optimisation, either using an automatic computer routine, or by trial-and-error. Since there was only one parameter to optimise here, the latter method was quite acceptable.

11) Accuracy

The selection of a criterion model accuracy is also an important aspect

of the model calibration procedure, since it provides the basis for the adjustment of parameter values. Even for a single output like 'stream discharge', there are several aspects of the output which may interest us: total runoff; peak discharges; timing; etc. Here, we have sought to minimise the difference between the sum of the squares of the differences between the observed and simulated outputs:

$$F = [c(Q_{obs} - Q_{pred})^2]$$

where

F = the objective error function

Q_{obs} = the observed discharge, and

Q_{pred} = the predicted discharge.

However, we were also interested to check on differences in runoff volume (we call the difference in predicted and observed total runoff 'D'), and timing although since discharge is predicted in hourly steps, there is less flexibility here.

It was decided to concentrate initially on the storm of 9/10 September 1983, since the rainfall records for this storm have already been analysed in some detail. The value of 'c' could then be set by optimisation and checked against the 'process' parameter value derived from hydrograph analysis. Although it is not by any means ideal to calibrate using just a single hydrograph, this was in fact done, mainly because it simplified the programming considerably. Two lengths of record could have been used: either the entire hydrograph which resulted from the rainfall (54 hours), or a shorter record covering the 'radar' rainfall period only (14 hours). Using 54 hours, the optimal value of

'c' was 0.20, very close to the calculated ROP (table 7.1a). The coincidence is slightly misleading, however, since this value of 'c' underestimates the total runoff produced. A value of 0.28 is needed to produce similar runoff totals. Of course, the total runoff should be correct, given that we know the real value of 'c'. This suggests problems with the accuracy of either the rainfall or runoff data: in fact, only one gauge could be used to calibrate the 54-hour record, this being B5 which records the lowest total for any of the catchment gauges during the main part of the storm (note that ROP was calculated using data from a number of gauges). Using higher rainfall values in the simulation model would clearly raise the predicted total output. This suggests that 'F' (though most commonly used) is a less useful objective function than 'D' in this instance, although the former has the advantage of being sensitive both to timing and absolute discharge.

For the shorter period of 14 hours (during the main time of rainfall), the optimisation is much more satisfactory (table 7.1b). The optimal value 'c' for both objective functions is 0.17, only a little below the estimated ROP. This optimisation was achieved using data from all the gauges in the Upper Derwent basin: the predicted hydrograph should be very close to the observed, since we are using the maximum amount of rainfall information available, and any outstanding error must relate to the imperfections of the model structure and not to the errors inherent in the input data. The 'optimal' predicted hydrograph is tabulated on table 7.2: several points are notable. The low intensity rainfall in the early stage of the storm produced too much runoff in the model; some infiltration threshold needs to be incorporated into the model structure perhaps. For the same reason, the main discharge

peak is overpredicted. The model has no baseflow component, so the predicted discharge returns much too quickly to prestorm discharge levels. Again, this could be rectified by modifying the model to include a baseflow recession coefficient (see Anderson and Burt, 1981) which would be based on observed rates of recession flow decline. It is also apparent from the hydrograph that the runoff coefficient increases during the storm (for well-documented reasons). Thus the predicted peak comes earlier than the observed peak, probably not because of reasons of streamflow routing, but because of soil moisture controls. This could perhaps be rectified by making 'c' dependent on rainfall intensity. However, despite these imperfections in the predicted output, the two hydrographs on table 7.2 are surprisingly similar, perhaps much closer than some of the scathing comments made about time-area models would suggest was possible! We might offer the thought that the demise of such simple models was not just because of greater hydrological insight, but that also the advent of computers led us into the world of physically-based, complex mathematical models without fully developing these more simple types of model which, though mathematically much simpler, are still tedious to calculate without recourse to a computer. There may be some merit in the use of such models, at least as a preliminary analysis of a basin for which not a great deal of information is available.

Of course, the main purpose of this simulation exercise was not simply to replicate the observed hydrograph for a single storm but to investigate the effect that differences in the distribution of rainfall has on the predicted output. We might expect that as our knowledge of the rainfall distribution becomes more uncertain, so will our prediction

if the storm hydrograph. We might also wish to know to what extent a major enhancement of rainfall in the highest parts of the catchment will affect the outflow hydrograph. These points are investigated in the following paragraphs.

Uncertainty about rainfall information

Two approaches are possible when investigating the quality of rainfall data being input to a runoff model:

i) Data on table 7.3 resulted from comparing simulated hydrographs (for the 9 September storm event) using no more than three gauges with the hydrograph simulated when using ALL the catchment gauges. In a sense, these results define the additional error which results, not because of the model structure, but because of the uncertainty in input data. The results on table 3 show that objective function 'D' is largely dependent on the total rainfall caught by the gauge(s), but is also influenced by the time-distribution of the rain. Thus gauge E12, which recorded a total of 40.7 mm but with 16 mm in one hour, greatly overestimates the total discharge. Gauge A1, whilst having a total of 36.7 mm, has a more even distribution of rain and the overestimation is less. Function 'F' is less easy to interpret: it seems in part to depend on total rainfall, but the pattern is not entirely consistent, and other factors such as location within the basin, or gauge altitude, could be influential. Since the Upper Derwent is only 17 km², the gauges all have very similar hyetographs and so their discharge predictions are quite similar too. In very large catchments we might expect much more error to occur as our uncertainty about the rainfall distribution increases - particularly if the number of raingauges is also reduced.

In the Upper Derwent, only E12 provides an unsatisfactory prediction of storm discharge: this gauge caught the edge of a storm cell that was mainly to the east of the catchment and so had higher total rainfall than the other gauges. For the prediction using ALL the gauges, the effect of E12 is important to include but is clearly not dominant. This example illustrates the potential danger of using only one gauge, even in a small basin, if that gauge is unrepresentative of the basin as a whole. At the least, a gauge must be representative of the total and timing of the rain: thus, the Snake Data Logger, whilst several kilometres to the west of the Upper Derwent, gives a prediction which is no less acceptable than those from several of the single gauges within the basin. It is worth noting that the use of three gauges - one in each time sector of the basin - gave no benefit, although the use of more than one gauge will be more necessary as the size of the catchment increases. No obvious 'rules' emerge about how to rationalise the siting of a single rain gauge so as to be representative of basin rainfall as a whole. Perhaps the results on table 7.3 suggest that a gauge (e.g C8) should be in the upper/central part of the basin, but this is very much a tentative conclusion at this stage.

Finally, we can note that, as expected, the radar estimates give unacceptable errors in the prediction of hydrograph dimensions because of their marked underestimation of rainfall intensity.

ii) Data on table 7.4 resulted from comparing simulated hydrographs with the observed record for the gauging station. Again objective function 'D' is quite simple to explain, whilst 'F' is not. Note that some single gauges have lower F values than that for 'all gauges'; this

must reflect the simplicity of the model structure rather than the quality of the rainfall data, but it does show how the two components of modelling interact, not always with clear results! Note that when ALL gauges are used, the 'D' value is minimised; this seems a significant factor in favour of maximising rainfall information where possible. However, some individual gauges do record slightly lower values of 'F', although there seems no consistent pattern involved - both high and low, central and peripheral gauges have a low 'F'. Again, the failure of rainfall-radar to detect the high rainfall intensities generated over the Pennine hills in this storm is emphasised: consequently the total rainfall is greatly underestimated and the model predictions are inaccurate.

Both types of comparative exercise have their merits: comparison with the 'maximum information' prediction does show the increase in uncertainty which exists when there is less information available, but as table 7.4 shows, in a small catchment there is relatively little error involved compared to the observed hydrograph, except where one gauge is affected by localised raincells (eg. E12). Thus, the most accurate predictions are made when all the gauges are used, but when only a single gauge is used, it is a matter of chance as to whether the results are accurate or not. Obviously, a 'representative' gauge must reflect the pattern of rainfall, both temporal and spatial, over the basin. This is, of course, quite likely to be the case in a basin of 17 km². In upland areas, intense localised variations are unlikely to occur, and in frontal rainfall when orographic enhancement is likely, these spatial variations seem likely to be evened out over a basin the size of the Upper Derwent at the timescale of one hour (see also section 6.4).

The following examples suggest that localised enhancement may not be all that influential although any general increase in rainfall over the hills must be detected.

Simulating the role of enhancement over the highest parts of a basin

Two examples are presented that illustrate the possible influence of orographic enhancement of rainfall intensity over high ground. One is hypothetical, whilst the other uses the storm rainfall pattern for 18 August 1983, a storm which had a much clearer pattern of local enhancement than the 9 September storm which we have discussed in such great detail.

i) Burt (1980) showed that a significant pattern of orographic rainfall could be detected over the Pennines once a rainfall gradient of 2 mm rain per 100 m height was developed. Using this gradient over the Upper Derwent, this would mean 1 mm for A-level gauges, rising to 5 mm for E-level gauges. Taking a baseflow discharge of 1 cumec., 5 hours rainfall at the appropriate intensity was input to each 'gauge area'. Having produced an output hydrograph for 'all gauges', a reduction in information was then imposed. Results are given on table 7.5. As (now) expected in a small catchment, if the individual gauge total is close to the basin mean (ie. resembles the overall pattern), then the hydrograph is closely replicated. Both low and high gauges are inaccurate. The Upper Derwent is not large enough that travel times significantly affect the runoff pattern, except perhaps by an hour. In a much larger basin, there would be no guarantee that a gauge with mean storm rainfall would mirror the 'all gauge' hydrograph, simply because the spatial distribution and, by implication, the timing of the rainfall over the

basin, would then be significant. In a sense this may be self-evident, but we began this project believing that even in a basin as small as 17 km^2 , there would be significant control exerted on the storm hydrograph by the pattern of the rainfall distribution. Both field and simulation results suggest that this may not be so, except for the case of intense thunder cells.

ii) The second example takes the storm of 18 August 1983 which contained a clear local pattern of orographic enhancement, probably triggered by convectional instability as the air mass moved over the Pennine hills (figure 5). The rainfall totals decline from the northwest (highest) corner of the basin (28.3 mm at C8; 24.2 at E14) to the south-east of the basin (9.7 mm at E12); distance from the western escarpment rather than actual gauge altitude seems to be the main control of the rainfall distribution. Maximum hourly intensities range from 6.6 mm at C8 down to 2.1 mm at E12. Only 9 gauges were operational in this storm, as shown on table 7.6, but this is sufficient for the simulation exercises which follow. The model was first run using all available rainfall data; following runs compared predictions based on less rainfall information with this initial hydrograph. Results are given on table 7.7. It is clear that the central gauges, such as A2 or C9, again provide the closest replication of the 'all gauge' hydrograph. It might be thought that the high, western gauges, such as C8, where high intensities were recorded, would have a significant influence on the overall output: however, this seems not to be the case. Again, these results seem to confirm that when locating a raingauge, even in a small catchment like the Upper Derwent, it is most important to record the 'average' rainfall input, and there may be much less need to require the use of remote

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TOPOGRAPHIC CONTROLS ON RAINFALL AND RUNOFF (U)
HUDDERSFIELD POLYTECHNIC (UK) DEPT OF GEOGRAPHY
T P BURT ET AL. MAR 86 DAJAS7-81-C-8819

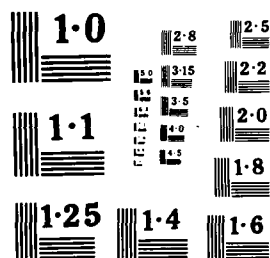
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(=costly) gauges to monitor high-intensity, but local, raincell enhancement.

In order to investigate this last point in more detail, further simulations were run, based on the 18 August storm rainfall record, but allowing for additional rainfall enhancement in the upper, western part of the basin. To achieve this 'increase' the rainfall in the upper time-area was multiplied by a coefficient 'U', and rainfall in the middle time-area was multiplied by a coefficient 'V' whose value was half-way between U and 1. All runs were based on the E12/E15/E14 combination as listed on table 7.7. In the first series of runs, only 'U' was varied, but in the second set both 'U' and 'V' were varied. Results on table 7.8a show that local enhancement in the upper time-area (only 1.13 km²) produces little effect. Even when rainfall at E14 is increased threefold, the overall basin rainfall only went up to 18.8 mm from 15.6 mm, and the 'F' value remains very low. However, as shown on table 7.8b, when the enhancement affects nearly half the catchment then increases in 'U' and 'V' together rises above 1 and the basin mean rainfall has risen by one third to 21.7 mm. As long as a single gauge is positioned to detect such a general pattern of enhancement, the time-area model suggests that reasonably accurate simulations will result, and that there is no need to worry about local increases above this general level. Of course, for a localised storm when no rain occurs elsewhere, we would reach a different conclusion; but, our concern here is with upland rainfall and for this, a less dense network of gauges seem allowable in the Upper Derwent than we originally envisaged. Spatial and temporal variations in the pattern of orographic rainfall are again suggested to be less than we might have expected, both on

field evidence, and now on the basis of simulation modelling. It would be interesting to see if the use of a more sophisticated model (eg. HEC1) confirms this conclusion.

Finally, some critique of this whole exercise is demanded. The modelling exercise suffers from several deficiencies even though the quality of the input data is very high: the catchment is too small to exploit fully spatial variations in storm rainfall; the time-area model is an extremely simple one; the model has been calibrated using only one storm event - a minimum of 20 hydrographs would be used in any forecasting exercise (remember that a value of $C = 0.2$ resulted from a larger data set); finally, only certain aspects of the output have been considered in these tests, with timing and hydrograph shape not examined in much detail. However, the results have proved of some interest and may suggest that simulation modelling makes a valuable prologue, rather than epilogue, to field research.

Table 7.1 Optimisation of the time-area model parameter 'c' for the Upper Derwent catchment, using the storm hydrograph of 9 September, 1983.

a) Using 54 hours discharge data and rainfall from gauge B5.

C	F	D
0.15	47.71	-86788
0.175	43.89	-70624
0.20	43.18	-54450
0.225	45.61	-38296
0.25	51.13	-22136
0.275	59.79	-5979
0.30	71.56	10177

..... * optimal solution for F

b) Using 14 hours discharge data and rainfall from all basin gauges

C	F	D
0.10	20.27	-38700
0.125	13.58	-25228
0.15	9.84	-11761
0.165	9.02	-3675
0.17	8.98	-990
0.175	9.06	1706
0.18	9.26	4399
0.20	11.24	15174
0.225	16.39	28641
0.25	24.49	42112
0.275	35.56	55584
0.30	49.58	69044

..... * optimal solution for F

Table 7.2 Predicted and observed storm hydrographs for the Upper Derwent using 14 hours discharge data, all basin raingauges, and the optimised 'c' value of 0.17.

	Hour	Qpred	Qobs
9th Sept 10th	23.00	0.079	0.079
	00.00	0.652	0.079
	01.00	1.192	0.080
	02.00	0.805	0.082
	03.00	0.816	0.096
	04.00	2.545	0.179
	05.00	5.666	4.504
	06.00	4.586	4.934
	07.00	2.934	4.044
	08.00	2.533	4.291
	09.00	2.749	4.589
	10.00	1.823	3.698
	11.0	0.605	2.693

C = runoff coefficient

F = sum of squares of differences between Qobs and Qpred

D = difference between predicted and observed total discharge

Table 7.3 Error analysis of simulated storm hydrographs for the Upper Derwent catchment, using the time-area method. The 'observed' hydrograph is taken to be that simulated when all available rainfall information is used.

Gauges used in simulation	F	D	Total rainfall at gauge (mm)
A1 only	1.59	11811	36.7
A2 only	4.85	-2498	32.2
A3 only	4.86	-7052	30.3
B4 only	4.94	13435	37.2
B5 only	3.39	-16797	26.5
B6 only	4.86	-7052	30.3
C7 only	0.348	4917	34.2
C8 only	1.43	-4960	30.9
C9 only	3.07	6206	34.7
D10 only	6.29	4863	34.3
D11 only	3.07	6206	34.7
E12 only	18.40	23922	40.7
E13 only	2.59	-1043	32.2
E14 only	2.75	-16250	26.7
E15 only	3.43	-5295	30.7
B5, A3, E14	3.56	-12830	-
Radar-rainfall	54.73	-70671	6.68
Snake Pass logger	14.99	-12848	28.0

F = sum of squares of differences in discharge levels

D = difference between predicted and observed total discharge

Gauge letters indicate altitude: A - lowest; E - highest

Table 7.4 Error analysis of simulated hydrographs, for the storm of 9 September 1983 in the Upper Derwent catchment, using the time-area method. The 'observed' hydrograph is the recorded hydrograph at the Slippery Stones gauging station.

Gauges used in simulation	F	D
All gauges	8.98	-990
A1 only	9.43	10821
A2 only	17.25	-3488
A3 only	16.84	-8042
B4 only	9.03	12445
B5 only	16.15	-17787
B6 only	16.84	-8042
C7 only	9.15	3927
C8 only	7.69	-5950
C9 only	7.66	5126
D10 only	20.01	3873
D11 only	7.66	5216
E12 only	34.99	22932
E13 only	15.23	-2033
E14 only	8.52	-17240
E15 only	7.20	-6285
B5, A3, E14	15.82	-13820
Radar-rainfall	58.03	-71661
Snake Pass gauge	17.89	-13838

Table 7.5 Simulation results for a hypothetical storm over the Upper Derwent

a) Results using all gauges:

Time (hrs)	Discharge (cumecs)
4	1
5	1
6	1
7	2.092
8	3.205
9	3.472
10	3.472
11	3.472
12	2.379
13	1.266
14	1
15	1

b) Comparison with 'all gauge' hydrograph

Gauge used in simulation	F	D
A3 only (1mm/hr)	11.968	-30042
B5 only (2 mm/hr)	3.21	-15584
C7 only (3 mm/hr)	0.11	-1127
D11 only (4 mm/hr)	2.655	13338
E14 only (5 mm/hr)	10.847	27792
Area weighted mean (3.08 mm/hr)	0.105	36
B5..A3..E14	4.95	-18608

Rainfall duration - 5 hours

Intensity - 1 mm/hr at A-level rising to 5 mm/hr at E-level

Baseflow discharge - 1 cumec

'c' = 0.17

Table 7.6 Hourly rainfall totals for the storm of 18 August 1983

Gauges :

E14	E15	C8	D11	C9	A2	A1	D10	E12
0.7	0.7	1.6	0.5	0.4	0.2	0.1	0.2	0.3
0.6	0.5	0.4	0.2	0.2	0.2	0.1	0.2	0.1
0.8	0.4	1.5	0.4	0.4	0.3	0.7	0.3	0.6
1.2	1.1	1.9	0.8	0.8	0.7	0.7	0.6	0.6
1.2	1.1	1.5	1.1	1.2	0.7	1.3	0.5	0.5
1.6	1.1	3.0	1.0	0.9	0.7	1.5	0.6	1.5
4.5	3.6	5.1	3.3	3.2	1.9	2.5	2.2	1.9
2.6	3.3	3.1	2.7	2.8	2.0	2.0	1.6	2.1
5.1	4.2	6.6	3.8	3.8	3.0	4.0	2.8	2.0
3.7	3.6	2.5	2.9	3.0	2.2	1.5	1.7	0.1
1.7	1.6	0.6	1.1	0.9	0.8	0.5	0.8	0.0
0.2	0.2	0.1	0.1	0.1	0.5	0.1	0.1	0.0
0.2	0.1	0.3	0.1	0.1	0.1	0.0	0.1	0.0
0.1	0.2	0.1	0.3	0.6	0.3	0.0	0.5	0.0
24.2	21.8	28.3	18.3	18.4	13.6	15.0	12.2	9.7

Notes:

- i) Gauges are tabulated in approximate position from NW to SE
- ii) Gauge totals given at foot of column
- iii) Values given are hourly totals for the main part of the storm.

Table 7.7 Simulation results for the storm of 18 August 1983

a) The simulated hydrograph using all available rainfall data

Time (hrs)	Discharge (cumecs)
4	1
5	1
6	1.557
7	1.823
8	1.99
9	2.578
10	3.31
11	3.548
12	3.333
13	2.546
14	1.675
15	1.164
16	1.133

b) Comparison with 'all gauge' hydrograph

Gauge used in simulation	F	D
A1 only	0.967	-7430
A2 only	1.686	-11862
C8 only	8.496	24469
C9 only	0.216	875
D10 only	2.681	-16182
D11 only	0.192	706
E12 only	6.356	-23180
E14 only	3.06	15757
E15 only	1.345	9580
A2..E15..E14..	6.727	21913
E12..E14..E15	0.978	-7415

Table 7.8 Simulations for the storm of 18 August with additional enhancement of rainfall intensities in the western area of the catchment.

a) Enhancement in the upper time-area alone :

U	F	D	Basin mean rainfall total
1	0.978	-7415	15.607
1.1	0.929	-6976	15.767
1.3	0.843	-6083	16.089
1.5	0.772	-5191	16.411
1.7	0.719	-4298	16.732
2	0.669	-2959	17.214
2.25	0.659	-1850	17.617
2.5	0.672	-734	18.018
3	0.779	1490	18.822

b) Enhancement in the upper and middle time-area :

U	V	F	D	Basin mean rainfall total
1	1	0.987	-7415	15.607
1.1	1.05	0.762	-5767	16.213
1.3	1.15	0.504	-2465	17.425
1.5	1.25	0.477	842	18.638
1.7	1.35	0.682	4132	19.850
2	1.5	1.425	9086	21.668
2.25	1.63	2.422	13215	23.183
2.5	1.75	3.820	17344	24.699
3	1.5	7.665	25596	27.730

Chapter 8 Summary and Conclusions for Future Work

8.1 Topographic controls of rainfall distribution

The results of the field study were analysed at two scales: that of the Upper Derwent basin (17 km^2), and the southern Pennine region (of about 2500 km^2). At the small basin scale, total storm rainfall was significantly correlated with general topographic indices (not with gauge height itself) for a variety of synoptic conditions. This shows that orographic rainfall is not influenced by local (site) topography. For 15-minute and hour periods, the likelihood of significant correlations between rainfall total and altitude is much less; clearly more rain in total is produced over the highest ground but movement of raincells over the basin complicates the picture for shorter timescales. Even when feeder-seeder mechanisms occur, the highest rainfall may occur downwind of the highest ground, although the addition of up to 3 mm per hour at such times is notable in itself. Overall, the field results suggest that prediction of within-storm rainfall distributions in small upland basins becomes more difficult as the convective component of total rainfall increases. Repeatable patterns of storm total rainfall were found at the Upper Derwent scale, but these were associated with regional rather than local topography. The cause of the variation in the Upper Derwent could be ascribed to raincells within fronts or to storms which were convective in origin; the latter are particularly unpredictable. Therefore, for any air mass incorporating a convective element, the degree of conditional instability will determine the predictability of the rainfall pattern. Only pure orographic (feeder-seeder mechanism) rainfall can be predicted, and the Upper Derwent is too small to allow such patterns to be seen.

The runoff modelling described in chapter 7, although somewhat simplistic, did suggest that the scale of rainfall variation observed within the Upper Derwent basin at the one-hour timescale was not significant with respect to the predicted storm hydrograph, provided that mean basin rainfall is accurately gauged (which is, in itself, a major problem, as noted above). We began the project by believing, even in a basin as small as the Upper Derwent, that there would be significant control exerted on the storm hydrograph by the pattern of the rainfall distribution. Simulation results, for the range of variation observed in the field, suggests strongly that this is only likely to be important for localised thunder cells. For a small basin, it does not seem important to detect the movement of raincells therefore, but to concentrate on the general pattern of rainfall at longer timescales. We make the recommendation that hourly basin-mean rainfall is the crucial factor and this can be adequately calculated for all but entirely convective storms using three strategically placed raingauges.

At the southern Pennine scale, the majority of storms showed a significant correlation between topography and rainfall total, as expected. There was little opportunity to examine the 'pure' enhancement process involving feeder-seeder mechanisms; for three events at the end of 1983, enhancements of up to 3 mm per hour were noted, but there was too little data available to be able to say whether the pattern was consistently related to altitude throughout the storm. For the 9.9.83 storm, analysed in some detail in chapter 6, it is clear that intense rainfall is likely to be triggered by convectional instability over high ground, but its precise location and movement cannot be predicted. Thus, a general correlation with topography results, but

the precise local pattern is open to some doubt. The best correlations between rainfall and altitude seem to involve storms where fronts pass over the Pennines. However, too few storms were analysed at the regional scale to be able to confirm this or to be able to predict the rainfall gradient on the basis of synoptic conditions. However, rainfall gradients in 'orographic' storms were often in the range 2-3 mm total per 100 metres rise. This would produce a significant fall over the high ground and would be hydrologically very important when predicting storm hydrographs for large rivers draining from the area. As with the Uppr Derwent, runoff prediction at the regional scale requires accurate knowledge of the rainfall over the high ground; probably one-hour totals would be sufficient but modelling studies would be needed to confirm this point. Once again, the use of calibrated radar, or telemetering raingauges alone, seems vital to flood forecasting in such upland areas.

8.2 Rainfall radar

Analysis of one case study suggests that rainfall-radar is capable of detecting orographic rainfall when convective instability has been triggered, and is accurate (even when not calibrated by actual raingauge data) where the clouds are high. The radar was still successful in predicting the pattern but underestimated the totals when low-level enhancement processes were occurring over the hills. This is an important defect since this type of enhancement occurs frequently. Further research is needed into the use of radar for predicting rainfall totals and storm runoff in upland areas. If calibrated in real time using telemetering raingauges, radar should prove invaluable, particularly given the difficulties of operating a raingauge network in the harsh and remote upland environment. The radar study also confirmed that the

Upper Derwent is too small a scale at which to study "pure" orographic enhancement. Finally, it should be noted that any further radar study of this sort should incorporate the original digital radar data: this would facilitate a much more extensive study than was possible here, given the immense amount of time it takes to decode the radar scan hard-copy.

8.3 The scale of orographic enhancement

With hindsight, the study was ill-conceived in that it assumed that a drainage basin of 17 km^2 was large enough in which to detect significant spatial and temporal variations in rainfall pattern which would be of hydrological importance. It is true that rainfall does vary at the Upper Derwent scale, but its effect is not important to the storm hydrograph, both because of the insensitivity of the hydrograph and because of the very local nature of the rainfall variation. Much clearer spatial variation can be detected at the regional scale; study at this scale would have been much easier since all gauge sites could have been adjacent to roads. In planning the scale of study, the choice of a catchment scale was necessary to aid the runoff modelling studies; the Upper Derwent has a clear enough pattern of annual rainfall but at the storm and intra-storm scale this variation, whilst still present, is not hydrologically significant. This could perhaps have been anticipated if simulation models have been used as a precursor to the field studies. However, given the absence of field data at that time, and the assumption that such models can realistically simulate runoff processes in this scale of catchment, such simulation exercises might still have proved inconclusive.

8.4 Future work

Future studies should concentrate on rainfall patterns at the regional scale and should integrate rainfall-radar from the outset. Choice of raingauge sites close to roads would still provide a sufficiently dense network in the remoter uplands, and would be much easier to operate. Use of data logger gauges is also recommended where possible (though in this study the deep peat soils precluded such a design) since they are more reliable than clockwork mechanisms and yield immediate data, unlike autographic gauges whose charts must be analysed by hand, a process which again (like operating a remote raingauge network) which involves a considerable investment of time. It seems clear that "orographic" rainfall (in the traditional sense) hydrologically important at the regional scale, but further study is needed to quantify this effect and to help answer the question as to how far orographic enhancement is predictable in time and space. This study has perhaps raised more questions than it has answered, but it has at least shown that STORM rainfall is related to the general topography of an upland area, and suggests that such rainfall is likely to be hydrologically significant for large rivers in the Pennine region.

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